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A BOLOMETRIC STUDY OF THE SOLAR CORONA.

By invitation of Director Campbell of the Lick Observatory an expedition in charge of the writer was sent by the Smithsonian Institution to join with the Crocker eclipse expedition to Flint Island. In all matters of transportation, subsistence, and companionship the writer and his assistant, Mr. A. F. Moore, were cared for by Director Campbell as if members of his own staff; but the expenses of the Smithsonian party were paid in full by the Smithsonian Institution.

OBJECTS AND METHODS.

We proposed to measure with the bolometer the intensity of the radiation of the solar corona and to determine the quality of coronal radiation as compared with that of the Sun.

In the year 1900 the first bolometric observations of the corona were made by Smithsonian observers,¹ and from these observations certain inferences were drawn by different authors as to the quality of the radiation of the inner corona.

All bodies by virtue of their temperatures emit radiation; but it is only when the temperature is fairly high that any considerable part of the radiation is visible. The higher the temperature the larger proportion of the radiation caused thereby is visible.

All bodies exposed to radiation reflect some fraction of it diffusely but thereby generally alter the quality of complex radiation. When the reflecting bodies are particles whose diameters are small compared with the wave length of light, they reflect the shorter wave lengths better than the longer ones, and thus tend to render a larger proportion of the radi-

ation visible. Larger particles and gross bodies like the Moon by reflecting generally alter the quality of radiation in the other direction, thus diminishing the proportion of visible light.

Visible light is sometimes emitted by bodies which are apparently far below the temperature of incandescence, as in the cases of electrical discharges, luminous insects, and others. Such radiation may perhaps be almost wholly visible, without much intensity in the infra-red spectrum.

In view of these considerations and others, the inferences drawn by the writer from the bolometric study of the corona made in 1900 were contrary to the view that the radiation of the inner corona is produced mainly by the incandescence of matter heated to high temperatures by reason of its proximity to the Sun, and more favorable to supposing that the coronal radiation is due largely to luminescence, or perhaps to the reflection of solar radiations by very small particles. Arrhenius came to a different conclusion, but he misinterpreted the position of the bolometer with respect to the coronal image. See last cited reference.

The bolometric observations at Flint Island were designed to test the inferences above referred to and to measure more definitely the quantity and quality of the coronal radiation.

APPARATUS.

A concave mirror of 50 centimeters diameter and only 100 centimeters focus, mounted equatorially and driven by a clock, served to produce a very intense image of the corona.² A small guiding telescope was attached to the mirror frame so that the observer might point the mirror toward any desired object.

¹ See *Astrophysical Journal*, 12, 71-75, and 366-375, 1900.
 "The 1900 Solar Eclipse Expedition of the Astrophysical Observatory," pp. 22-26. Washington, 1904.

Lick Observatory Bulletin, No. 58, or *Astrophysical Journal*, 20, 224-231, 1904.

Astrophysical Journal, 21, 194-195, 1905.

² The mirror was freshly silvered and polished on the day before the eclipse.

In the focus of the mirror was placed the bolometer. A glass plate 3 millimeters thick was fixed close to the bolometer between it and the mirror, so that the radiation examined was thereby limited to wave lengths less than about 3μ . This device prevented any exchange of rays of long wave lengths between the bolometer and the sky, such as produced negative deflections when the bolometer was exposed towards the corona in 1900.³ The bolometer had blackened platinum strips 8 millimeters long and 0.7 millimeters wide, and of 0.5 ohms resistance. A metal diaphragm with circular aperture of 1 millimeter diameter was fixed between the glass plate and the central bolometer strip, so as to limit the region of the corona examined at each observation to an angular area of about $3'$ of arc in diameter.

About 10 centimeters in front of the bolometer was a self-closing blackened metal shutter which cut off the beam except when designedly opened. The opening of this shutter therefore exposed the central part of the bolometer to such rays as are transmissible by glass. Between the shutter and the glass plate and close to the latter was a special screen composed of a thin stratum of asphaltum varnish laid on one side of a plane parallel glass plate 3 millimeters thick. This screen was held out of the beam by a spring, except when designedly interposed. Its property when used was to cut off nearly all the visible part of the radiation, while transmitting nearly all of the infra-red rays transmissible by glass. The transmissibility of this screen for rays of different wave lengths follows:

	μ	μ	μ	μ	μ	μ	μ	μ	μ	μ
Wave length	0.50	0.55	0.60	0.65	0.70	0.80	1.00	1.2	1.6	2.0
Transmissibility	0.00	0.01	0.04	0.10	0.20	0.41	0.66	0.80	0.9	0.92

By interposing this absorbing screen the proportion of the observed radiation which lay in the infra-red spectrum could be roughly determined. Various trials made on Flint Island showed that ordinary sun-rays comprised from 29 to 37 per cent. of rays transmissible by this screen, depending on the humidity of the air and the altitude of the Sun; whereas sky-rays had only about 20 to 25 per cent. of transmissible rays. Moon-brightness (and by this is meant reflected sun-rays, not rays proper to the Moon itself, for such were eliminated by the glass plate) was examined on one occasion and showed a transmissibility of about 50 per cent.

Several diaphragms were provided for graduating the aperture of the concave mirror. The apertures of these diaphragms were knife-edged, and those of less

than 1 centimeter diameter were adjusted to lie within 3 millimeters of the silvered surface of the mirror. Allowing for the portions of the mirror shaded by the bolometer and its adjuncts, the apertures available were as follows:

Area (sq. cm.)..	1618.	283.	62.	0.316	0.077
Factor	1.0000	0.1750	0.0383	0.000195	0.000048

The equatorial was set up at Flint Island on the beach at about 12 meters distance from the galvanometers used for observing the indications of the bolometer. Two galvanometers were provided, exactly alike in resistance and general construction, and arranged so that if at the last moment any accident should happen to one, the observer might pass at once to the other.⁴ A thatched hut shaded by palm trees sheltered the galvanometers and their appliances, and was found to give most satisfactory protection both from heat and rain. The galvanometers were each of 1.5 ohms total resistance, comprised by 12 coils all connected in series. The needle systems, of 30 needles each, had mirrors 1 mm. by 1.2 mm. and weighed complete .011 grams each. Acetylene lamps were employed as light sources, and the images of the narrow flames were read on ground glass scales 90 centimeters in front of the galvanometers. Resistances of 3, 8, 17, 45, 200, and 1,000 ohms, respectively, could be put in series with either galvanometer to reduce its deflections if required. The corresponding factors of reduction are 2.0, 4.0, 6.0, 13.1, 60.0, and 300. These numbers were obtained by actual trial.

The Wheatstone's bridge of the bolometer comprised the two platinum strips of 0.5 ohms each, and two coils of 5.0 ohms each. These were enclosed in a wooden cylinder 7 centimeters in diameter and 18 centimeters long, itself shaded by a ventilated double-walled brass shield. A battery of 4 Gladstone-Lalande cells was used, furnishing a current of 0.4 amperes. This battery was located in the hut, and means for exactly balancing and trying the sensitiveness of the bolometric circuit were provided by joining to one galvanometer terminal and one battery terminal an adjustable resistance of about 500 ohms, acting as a shunt around one of the 5-ohm coils. It proved necessary to shade the copper cables connecting the bolometer with the apparatus in the hut, but after this was done the whole apparatus worked very satisfactorily, without prejudicial drift or wiggle of the galvanometer spot. When considerable changes of the pointing of the equatorial were made it was generally necessary to alter the balancing resistance slightly, as would be expected in consideration of the changed inclination of the bolometer strips. During the eclipse

⁴ This prudent measure was suggested by Mrs. Abbot.

³ Negative deflections in the experiments of 1900 were due to the fact that the sky was effectively cooler than the card shutter then employed, and not, as Deslandres has intimated, to some extraordinary rays which cool objects which absorb them.

the time of single swing of the galvanometer was 1.9 seconds, and a change of 1 ohm in the balancing resistance produced 250 millimeters deflection. This indicates that a rise of temperature of one bolometer strip of about $0^{\circ}00001$ C. would have produced 1 millimeter deflection at that time. These of course are far from the most sensitive conditions possible,⁵ but were regarded as good for a temporary installation.

The attention of the reader is invited to the following improvements in the apparatus of 1908 as compared with that of 1900:

1. One mirror replaces seven.
2. The uncertain exchange of radiations of long wave length between the bolometer and sky is eliminated by interposing glass.
3. Each observation is limited to a comparatively small angular area, well defined in position.
4. An absorbing screen for indicating the quality of the rays is introduced.
5. Means are employed for comparing in intensity the rays of the Sun, the sky, and the corona.

PRELIMINARY OBSERVATIONS.

The eclipse observations are of much more interest when considered along with other observations which have been made of the relative brightness and quality of Sun, sky, and Moon rays.

SUN-BRIGHTNESS, SKY-BRIGHTNESS, AND MOON-BRIGHTNESS.⁶

On December 29, 1907, one of the very few days during our stay on Flint Island when the sky was mostly free from clouds and of a good blue color for a considerable time, numerous measurements were made with pointings on the center of the Sun's disk and on many parts of the sky. In these measurements the full aperture of the concave mirror was employed for the sky, and the "0.316" aperture for the Sun. Sun-brightness was further reduced by interposing in the beam a rotating disk from which a sector of .045 the whole circle had been cut. Eight ohms resistance was placed in series with the galvanometer, under which circumstances 1 ohm change in the balancing resistance produced 55 mm. deflection. The measurements were begun about 9^h 40^m a.m., and continued till 10^h 40^m a.m., local time, so that the Sun was 20° - 40° from the zenith.

Reserving for another place a detailed study of

⁵ In Washington with a scale distance of 4 meters and a time of single swing in a vacuum galvanometer case of 7 seconds, a deflection of $\frac{1}{10}$ millimeter has been measurable. This corresponded to a rise of temperature of $0^{\circ}00000001$.

⁶ I propose to employ these terms for brevity, to mean the intensity of the radiation of the Sun, sky, or Moon, transmissible by glass, and therefore of less wave length than 3μ .

these and other comparisons of Sun and sky brightness, it will be sufficient here to state that the relative brightness of sky and Sun, equal areas being measured, varied from .0000031 at distant parts of the sky to .0000140 at 20° from the Sun. The average value was .0000062. It was impossible to secure accurate observations nearer the Sun than 20° , because the mirror could not be properly shaded from the Sun in such cases, and the diffused reflection of Sun-brightness would have masked the true sky-brightness.

Measurements made on Mt. Wilson in California⁷ in 1905-06 showed that the average ratio at that altitude was about .0000015, so that the sky at sea level appears to be roughly four times as bright as on Mt. Wilson.

From measurements made on December 27 at 3^h 30^m a.m., the Moon-brightness was about .0000012 of Sun-brightness, but this ratio can only be regarded as roughly approximate, and subject to alteration with the Moon's altitude, the humidity, and the haziness of the air.⁸

QUALITY OF SUN-BRIGHTNESS, SKY-BRIGHTNESS, AND MOON-BRIGHTNESS.

On December 26, with the Sun about 40° from the zenith, the ratio of the Sun-brightness transmissible by the asphaltum screen, to the total Sun-brightness was found to be 0.366; while for zenith sky-brightness the result came out 0.248. Owing to the change of humidity from time to time, with consequent large alterations of the intensity of the infra-red spectrum, ratios like these just given are not to be regarded as constants. In order to avoid errors from this cause, care was taken on eclipse day to determine the transmissibility of Sun-brightness immediately before and after totality, as will appear in its place.

On other days before the eclipse, values of the transmissibility ratio for Sun-brightness were obtained ranging from 0.29 to 0.37.

On the morning of December 27, at 3^h 30^m a.m., the transmissibility of the Moon-brightness was found to be 0.50.⁹ It is very significant to note that the day sky and the Moon, both reflecting Sun rays, alter the quality of Sun-rays in opposite directions, and in such marked degrees. The blue quality of the sky-brightness, as Lord Rayleigh has shown, is probably due to the fact that the reflection takes place from particles

⁷ Altitude 1,800 meters.

⁸ The ratio is not comparable directly with photometric estimations, nor with the bolometric ones of Langley, because the rays selected by the glass plate are neither visible rays alone, nor yet the total radiation.

⁹ See also Langley's comparison of the visible spectra of the Sun and Moon. *Memoirs National Academy of Sciences*, 3, 21, 1884.

small compared with the wave length of light, and principally perhaps from the molecules of air themselves.

In view of the data just given we should suppose that the brightness of the solar corona, if we imagine it to be caused merely by the reflection of ordinary Sun-rays, would be more transmissible to the asphaltum screen than Sun-brightness, if the reflecting particles are of gross magnitude, like those composing the surface of the Moon, but less transmissible than Sun-brightness, on the other hand, if the reflecting particles are minute like the molecules of gases.

OBSERVATIONS ON ECLIPSE DAY.

The approach of totality was uncommonly exciting on this occasion. Early in the morning the sky was overcast with thin high clouds, but these gradually grew thinner so that after 9 a.m. the prospects indicated a streaky sky containing something almost too thick for haze, but almost too thin for cirrus clouds. These prospects were fulfilled exactly during totality, but in the quarter of an hour next preceding, a thick cloud came up, rain fell fast from 11^h 08^m to 11^h 14^m, and the sky became clear of the low cloud only 15 seconds before totality at the Smithsonian station. The rapid change from fair prospects to completely discouraging ones, and the return of good conditions just at the critical time, will long be remembered. Our entire immunity from rain during totality was due to the fact that our station was about 1,000 feet north of the one occupied by the Lick Observatory.

At about 10^h 55^m and 11^h 45^m the following two series of observations were recorded on the brightness of the center of the Sun's crescents visible before and after the eclipse, respectively. In each series there was employed the 0.077 aperture, and also a series resistance of 200 ohms in the galvanometer circuit. The table includes actual readings on the galvanometer scale before and after opening the shutter of the bolometer, sometimes with, sometimes without the asphaltum screen. In reading the galvanometer the position of steady condition is first noted, then the farthest excursion of the spot of light after opening the shutter, which corresponds to the first swing of the galvanometer. In computing actual deflections no account has been made of drift of zero between the steady position and the end of the first swing, because this interval is only 2 seconds, and the drift was at no time rapid enough to be of import in this brief interval. During all these measurements of Sun-brightness the time of swing of the galvanometer was the same as employed during the total eclipse. The places on the Sun may be regarded as having been 0.7 radius distant from the center of the solar disk.

MEASUREMENTS AT 10^h 55^m.

Closed cm.	Open		Deflection	
	No screen cm.	Screen cm.	No screen cm.	Screen cm.
16.0	22.5		6.5	
16.0		18.2		2.2
16.3	22.8		6.5	
16.3		18.5		2.2
16.5	23.1		6.6	
16.5		18.8		2.3
16.6	23.3		6.7	
16.6		18.7		2.1
			Means	6.60
			Ratio	0.333

MEASUREMENTS AT 11^h 45^m.

Closed cm.	Open		Deflection	
	No screen cm.	Screen cm.	No screen cm.	Screen cm.
8.4	15.3		6.9	
8.6		10.9		2.3
8.4	15.3		6.9	
8.5		10.7		2.2
8.4	14.6		6.2	
8.4		10.7		2.3
8.4	15.4		7.0	
8.5		10.7		2.2
8.5	15.5		7.0	
			Means	6.80
			Ratio	0.331
Mean transmissibility of Sun-brightness 0.332				

MEASUREMENTS OF THE CORONA.

In the field of the finder telescope were cross threads, two of which intersected in the center making an angle of 75°. One of these threads was adjusted along the line of diurnal drift of the Sun, as found by stopping the clock of the equatorial. When the Moon's image was adjusted tangent to the threads, there were four positions available, according as the Moon occupied one of the obtuse angles or one of the acute angles between the intersecting threads. During the eclipse, measurements were made of the corona-brightness at the two positions of tangency in the obtuse angles, and one measurement was made in one of the acute angles. Besides these three positions two others were employed, situated 1:5 of arc beyond the extremities of the Moon's east and west diameter, and one position in the center of the dark Moon, making six in all. In view of the symmetry of the results to be given, and of the uncertainty of precise setting on so small an image with the bolometer, it seems unnecessary to specify the first three positions more definitely than to add that in the two positions of obtuse angle tangency the bolometer was central on points 4' of arc beyond the extremities of a lunar diameter inclined 52:5 to the east and west diameter,

and in the position of acute angle tangency the distance from the Moon's limb was about 12' of arc.

Let the six positions be designated in the order described above, as Positions I, II, III, IV, V, and VI.

The measurements are as follows:

POSITION I.				
Closed cm.	Open		Deflection	
	No screen cm.	Screen cm.	No screen cm.	Screen cm.
11.3	14.2		2.9	
11.2	14.5		3.3	
11.2		12.4		1.2
11.4		12.6		1.2
			—	—
		Mean	3.1	1.2
		Ratio	0.387	

POSITION II.				
Closed cm.	Open		Deflection	
	No screen cm.	Screen cm.	No screen cm.	Screen cm.
7.1	10.2		3.1	
6.9		7.9		1.0
		Ratio	0.323	

POSITION III.

No deflection whatever.

POSITION IV.				
Closed cm.	Open		Deflection	
	No screen cm.	Screen cm.	No screen cm.	Screen cm.
13.1	23.9		10.8	
13.6		17.3		3.7
		Ratio	0.343	

POSITION V.

Closed cm.	Open		Deflection	
	No screen cm.	Screen cm.	No screen cm.	Screen cm.
17.8	27.7		9.9	
19.0		22.8		3.8
		Ratio	0.384	

POSITION VI.

No deflection whatever.

On account of the number of observations the result in Position I is entitled to twice as much weight as that in Position II, and on account of the larger deflections observed, the results in Positions IV and V are regarded as each of twice the weight of those in Position II. It is not thought that the variations of the ratio of transmissibility between the several observations just noted are beyond the probable errors of the single determinations, so that without distinguishing separate positions the weighted mean result for the transmissibility of the inner corona-brightness may be regarded as 0.364. For positions I, II, the

mean is 0.366, and for positions IV, V, the mean is 0.362.

In order to determine the intrinsic corona-brightness as compared with Sun-brightness, we must first multiply the average solar deflections observed before and after the eclipse by the two factors appropriate to allow for the ratio of size of mirror apertures employed, and for the introduction of series resistance in the galvanometer circuit respectively. Performing this reduction and introducing also the data of sky-brightness already given we obtain the following values based on a Sun-brightness of 10,000,000.

Sun near zenith (Flint Island)	10,000,000
Sky 20° from Sun (Flint Island)	140
Sky distant from Sun (Flint Island)	31
Sky average (Flint Island)	62
Sky average (Mt. Wilson)	15
Corona Positions IV and V	13
Corona Positions I and II	4
Moon (Flint Island) about 50° zenith distance....	12 (?)

DISCUSSION OF THE RESULTS.

When we recall the extreme brightness of the sky within a single degree of the Sun as compared with that 20° away and consider also the figures just given, the proposal to observe the corona without an eclipse seems unpromising.

From the figures just given it appears that the corona of 1908 only equaled the Moon in radiation transmissible by glass, at the brightest observed part of the inner corona. Referring to the conclusions made by the writer from the bolometric observation of the eclipse of 1900, it will be recalled that it was assumed by him that the region of the corona then observed was equally as bright as the Moon visually. It now seems probable that this was not so, and accordingly the argument he made for an exceptional richness of visible light in coronal radiation, which depended on the assumption just referred to, is weakened. In actual fact the coronal radiation proves to be almost, but not quite, as rich in visible light as the ordinary solar radiation coming from points 0.7 radius from the center of the Sun's disk, as shown by the measurements of 1908 made with and without the screen.

PROBABLE NATURE OF THE CORONA.

The nature of the radiation of the inner corona has been supposed by some to be principally reflected solar radiation, by others principally due to the incandescence of particles heated by reason of their proximity to the Sun; by others principally luminescence, perhaps similar to the Aurora; and by some as a combination of all of these kinds of radiation.

A satisfactory theory of the corona must take cognizance of the following facts at least:

1. The color of the corona does not appear to change at varying distances from the limb of the Sun, and the transmissibility of its rays to the asphaltum screen is the same at 1:5 and 4:0 from the limb.

2. Its brightness is very small and falls off rapidly with increasing distance from the limb.

3. Its spectrum is mainly continuous near the limb, but shows dark Fraunhofer lines, more and more distinctly, at increasing distances therefrom. A few not very conspicuous bright spectral lines are present near the limb, and perhaps in the outer corona also.

4. Its light is polarized in the outer regions, but polarization grows less marked, and at length disappears near the limb.

5. Its brightness is almost, but not quite, as little transmissible to the asphaltum screen as that of the Sun itself; and far less so than the reflected brightness of the Moon, but far more so than the reflected brightness of the sky.

6. Any kind of matter so near the Sun must be hot, and must also reflect solar rays.

7. There is no evidence of high pressure in the corona.

The considerations (3), (5), and (7), taken together, are hard to satisfy. For if the inner corona were hot enough to give out a spectrum of incandescence satisfying (5), the matter composing it must be gaseous if it is like any matter we know of.¹⁰ Accordingly we should expect a bright line spectrum like that of the chromosphere if the inner corona shines chiefly by incandescence;¹¹ and furthermore we should expect its rays to increase in transmissibility to the screen, and grow red to the eye, with increasing distance from the Sun.

If we may suppose that the temperature of the corona is everywhere low enough to allow solid or liquid particles to be formed, then all the specifications excepting (3) are easily satisfied by the hypothesis of a corona of reflection.¹² Our knowledge is not sufficient to enable us to prove that the particles even

¹⁰ Arrhenius computes a possible temperature of 4620° at 0.7 from the limb, and then suggests that the matter there may be liquid drops. How is this possible?

¹¹ The gaseous material of the Sun itself is under enormous pressure, so that its spectrum is thereby made continuous. Not so the corona.

¹² Specification (4) is no obstacle, because the particles near the Sun receive light from a solid angle of nearly a whole hemisphere, and would therefore show no polarization in any particular direction, because partially polarized in all.

of the inner corona would be too hot to be mainly liquid (that is to say above 3000° to 3500°). If they were all gaseous, the rays reflected would probably be richer than Sun rays in visible light, and this would be contrary to (5). May it not be that while a large proportion of the particles of the inner corona is gaseous, a considerable proportion is liquid or solid? Then may not the light of the inner corona be mainly reflected, like that of the outer corona, but with the bright line spectrum of incandescent gases present in sufficient strength to nearly obliterate the dark Fraunhofer lines of the reflected Sun rays? The continuous spectrum of the incandescent solid and liquid particles present would tend to increase the transmissibility of the coronal brightness to the asphaltum screen; so that the opposite tendency of the diffuse reflection of the gaseous particles present would be counteracted. At increasing distances from the limb we may suppose the particles would be cooler, and mainly solid or liquid, so that incandescence would wane, and a dark line spectrum would gradually appear. Still the transmissibility and color would remain nearly unchanged, because the light would be still mainly reflected Sunlight, and the particles now so large as not to enrich the proportion of blue light, but rather slightly to decrease it.

As for the attractive hypothesis of electrical discharge luminescence, like that of the aurora, one hesitates to recommend recourse to a source so little known. So far as known, too, this hypothesis like the others, has difficulty to reckon with the character of the photographic coronal spectrum.

The cause of the corona-brightness seems very difficult to decide in view of conflicting considerations; but in the judgment of the writer, the hypothesis that it is mainly due to the reflection of ordinary Sun rays, but diluted by radiation of incandescence and perhaps also of luminescence, seems most tenable.

In conclusion it is a pleasure to acknowledge the great aid afforded by the Director and staff of the Lick Observatory expedition; the conscientious and able work of my assistant Mr. Moore; the intelligent and faithful assistance rendered on the day of the eclipse by Chief Yeoman Chase of the *Annapolis*, and the uniformly cordial and courteous attentions of Governor Moore and the officers of the *Annapolis*, and of many others during the time when the expedition was in transit.

C. G. ABBOT.