VISUAL MEASUREMENTS OF THE POLARIZATION OF THE SOLAR CORONA

Thesis by

Josef J. Johnson

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INTRODUCTION

Because of their important bearing on the study of the distribution of matter in the solar corona, measurements of the percentage of polarized light received from various regions of the corona havè been made at many eclipses. In spite of the advantages of photographic methods, visual measurements are still of value because of the very large discrepancy - supposedly due to the fact that the scattering of light by atoms or molecules varies inversely as the fourth power of the wave length - which has hitherto been found between photographic and visual results. An invitation to join the Japanese expedition to Losap Island in the eastern Carolines made possible the continuation of this study at the eclipse of February 14, 1934.

It was hoped also to attempt to confirm the work of Lyot in detecting coronal polarization without an eclipse, using the Lyot-type telescope constructed at Mt. Wilson by Pettit and Slocum, but the difficulty of securing a satisfactory mounting for the instrument has compelled postponement of this part of the program.

ABSTRACT

Visual polarization measurements were made at the eclipse of February 14, 1934, with a modified Lyot-type polarimeter attached to a four-inch equatorially-mounted refractor. The objective was stopped down to 1 1/2 inches to reduce polarization effects within the instrument. Distances from the moon's limb were measured by means of a cross-wire reticle in the focal plane of the eyepiece.

Five different points of the corona were investigated, all lying directly off the east limb of the sun and ranging in distance from the limb from 1 to 8.5 minutes of arc. The observed polarization rose rapidly from 17% at 1' to 26% at 4', remaining sensibly constant from 4' outward.

These values are considerably higher than those previously obtained by visual methods, but are lower than the values obtained photographically. Subject to confirmation at a future eclipse, these values will constitute important evidence in favor of Schwarzschild's theory that a large part of the light of the corona is due to the scattering of photospheric light by free electrons.

I. THE POLARIMETERS

The first instrument considered was a modified Cornu polariscope designed by J. A. Anderson for measurement of the polarization of the daylight sky and used also by H. D. Babcock for measuring the polarization of the night sky. It is described by Babcock[1)] as consisting essentially of a small plate of calcite 5 or 6 mm thick, having cemented to one side a glass screen containing a series of equal opaque and transparent strips. The width of each strip is made somewhat less than the separation of the two images of a point seen through the calcite plate. The glass screen is so oriented upon the calcite as to bring the two images of each transparent strip just into contact side by side. This results in there being an angle of about 45° between the strips and the principal plane of the calcite plate; the exact value of the angle is immaterial.

It is evident that if the incident light is wholly or partially polarized the strips will in general appear alternately light and dark. When the plane of polarization is at 45° to the principal directions in the calcite (parallel or perpendicular to strips) the illumination will be uniform, but if the angle is 0° or 90° (45° to strips) there will be a maximum contrast between the two sets of images, dependent upon the percentage of polarized light in the incident beam. In the

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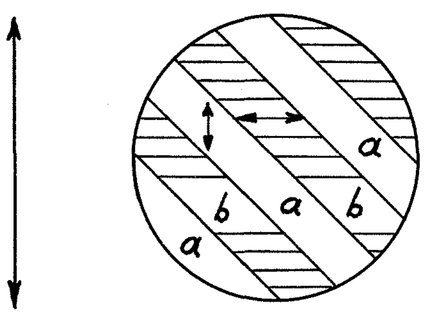
1) Harold D. Babcock, "Note on the Polarization of the Night Sky." Astrophysical Journal, 50, 228, 1919.

former case, all the light is divided equally between the two sets of images. In the latter, all the polarized light is present in one set of images while the unpolarized is equally divided between the two sets.

For quantitative measurements the calcite plate is used in conjunction with an analyser[2], which is free to rotate with respect to the plate about an axis joining the two. The entire assemblage may be rotated so as to place the strips at any desired angle with the plane of polarization of the incident beam.

This apparatus differs from that used in Cornu's original method for measuring the percentage of polarized light principally in having the alternate strips instead of a single aperture. The same analysis will apply[3].



Suppose the plane of vibration of one set of strips is made to coincide with the plane of vibration of the polarized portion of the incident light, as shown. Let a and b equal the amplitudes of the vibrations in the corresponding strips, a^2 and b^2 the intensities. If, in the incident beam, I_1 is the intensity of

2) In this instrument a double-image prism; ordinarily one would use a nicol.

3) R. W. Wood, Physical Optics, (1905) p. 240.

the natural light and I_2 the intensity of the polarized light, the proportion of polarized light will be given by

$$p = \frac{I_2}{I_1 + I_2}$$

But $\quad a^2 = I_2 + 1/2\, I_1 \quad$ and $\quad b^2 = 1/2\, I_1$

$a^2 + b^2 = I_1 + I_2 \quad$ and $\quad a^2 - b^2 = I_2$

$$\text{or} \qquad p = \frac{a^2 - b^2}{a^2 + b^2}$$

Call ω the angle between the transmission plane of the analyser and the plane of vibration in the strips a. Then the intensities of the two sets of images seen through the analyser will be $a^2\cos^2\omega$ and $b^2\sin^2\omega$. If now the analyser is turned until the adjacent strips are of equal intensity, we have

$$a^2\cos^2\omega = b^2\sin^2\omega$$

$$\frac{a^2}{b^2} = \frac{\sin^2\omega}{\cos^2\omega}$$

$$p = \frac{a^2 - b^2}{a^2 + b^2} = \frac{\sin^2\omega - \cos^2\omega}{\sin^2\omega + \cos^2\omega}$$

$$= -\cos 2\omega$$

It is to be noted that 2ω will be over 90°, since $\omega = 45^\circ$ when a and b are originally equal (incident light unpolarized.)

In rotating the analyser through 360° one finds four positions of no contrast. These positions are equally spaced, 90° apart, if the incident beam is unpolarized. In general they are unequally spaced, but they are always symmetrical with respect to the plane of vibration of the strips. Experimentally it is of course just as easy to measure the angle $180^\circ - 2\omega$ as it is the angle 2ω, thereby avoiding the inconvenience of considering angles larger than 90° in the reduction. In brief, then, the procedure is as follows: Remove the analyser; orient the instrument so that the strips are of uniform intensity. Rotate the instrument through 45° in either direction[4]. Replace the analyser and measure the smaller angle between the positions which give uniform intensity. The cosine of this angle equals the percentage of polarized light in the incident beam.

Fortunately this instrument was in Dr. Anderson's possession and was immediately available. Unfortunately, however, certain difficulties arose which prevented its use in the eclipse program. A number of trial measurements were made of the moon during the evenings of August 27-30, 1933, from the Astrophysics Building Observatory, using various optical combinations in connection with the polarimeter. It soon became evident that the light must be parallel as it passes through the instrument; that considerable magnification was necessary; but that placing the polarimeter behind the eyepiece of a telescope resulted in a hopelessly small field of view. Perhaps a compound telescope, with the polarimeter between the two components, could

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4) Since the minima are more sharply defined than the maxima, this procedure gives in general a more accurate setting for maximum contrast than could be obtained directly.

have been designed to overcome this difficulty; but as each optical surface tends to introduce extraneous polarization, and as such an instrument would be rather cumbersome and expensive, it was considered more expedient to build an instrument of the type designed by B. Lyot. Dr. Anderson's polarimeter later proved very useful, however, in checking the calibration of the Lyot instrument.

The Lyot polarimeter[5] is an instrument which compensates the polarization of the incoming beam by means of an inclined glass or celluloid plate, the proper inclination being determined by the disappearance of the fringes which are otherwise produced by a system of crossed calcite plates and nicol prism known as a Savart polariscope. Lyot's essential contribution was the introduction of a secondary plate designed to increase the sensitivity of the instrument[6] by detecting any slight residual polarization which remains after the beam has passed through the first plate. The secondary plate is so mounted that its normal may be inclined, in any position angle, to the axis of the instrument. The slight residual polarization is then enhanced or weakened according to whether the plane of polarization is parallel or normal to the plane of incidence. Such an instrument, illustrated in figure 1, was used by Lyot in analyzing the light of the planets. It is mounted in the place of the eyepiece of a telescope.

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5) B. Lyot. Revue d'Optique, 5, 108, 1926.

6) According to Lyot, one cannot ordinarily detect visually a proportion of polarized light smaller than 1%; this is approximately the minimum necessary for the appearance of the fringes in Savart's polariscope. He claims a sensitivity of 0.1% when his secondary plate is used.

The tube A is free to rotate within the telescope, its position angle being indicated by the scale C. The glass plate L_1 rotates about the axis DE; its inclination is shown by the position of the pointer F against the sector G, which is graduated in degrees from 0° to 65°. L_2, the secondary plate, may be rotated about the axis HI by means of the stem N. This plate is carried by the smaller tube J, which may be rotated within the larger tube. The collar K and the slot M are of such size that this motion is restricted to exactly 90°. The eyepiece O is mounted rigidly within the tube A. The polariscope P is contained in a cap screwed onto the mounting of the eyepiece. On the periphery of the cap are notches which may be engaged by the spring R to hold the cap stationary in such a position that the plane of the fringes is either parallel or normal to the axis DE.

In using the instrument the procedure is as follows: Set the plate L_1 perpendicular to the axis of the telescope. Adjust the telescope and the tube A so as to bring the image to the center of the field; focus for infinity. If now the plate L_2 is given a sufficient inclination, fringes will appear in the polariscope. Turn the tube J (carrying the plate L_2) so as to make it occupy in succession its two extreme positions. The fringes will remain of constant intensity only if the light is unpolarized or if the plane of polarization makes an angle of 45° with these extreme positions.

To determine the plane of polarization, it suffices to turn the tube A until the intensity of the fringes is the same for the two

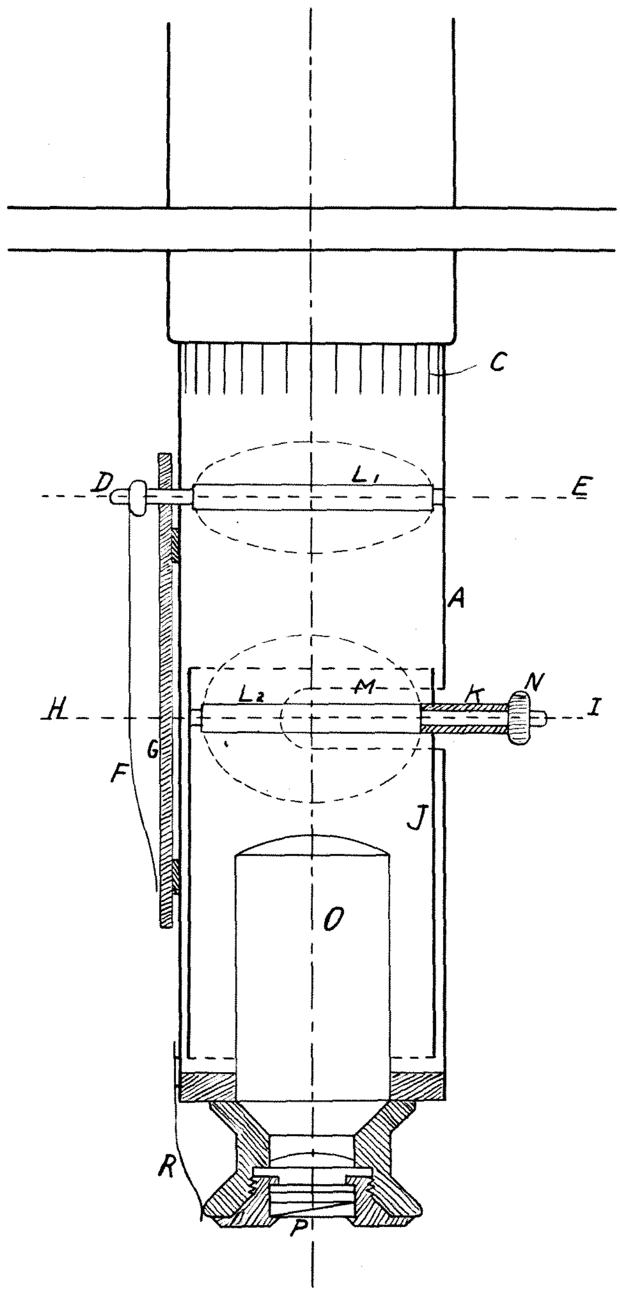

Figure 1

The Lyot Polarimeter

positions of the tube J, noting the position as given by the graduation C.

To measure the proportion of polarized light, turn the tube A through 45° in the proper direction to make the plane of incidence upon L_1 (as it rotates about DE) parallel to the plane of polarization found above; then incline L_1 to such a position that a 90° rotation of the tube J does not modify the intensity of the fringes.

The angle of incidence, as read on the sector G, gives the proportion of polarized light by means of a table which may be calculated from Fresnel's formulas. To make these calculations, it is necessary to keep account of the rays which undergo an even number of reflections from the two faces of the compensating plate when these are mixed with the direct rays, as is the case even when the plate L_1 has its faces parallel or perpendicular to the axis of the telescope. To avoid this effect, the glass plates may be replaced by sheets of celluloid about 1/100 mm thick, obtained by evaporation upon a glass plate from an amyl acetate solution and stretched tightly upon a frame, such as a glass plate perforated by a large hole.

These measurements may be made with great precision if the plate L_2 is inclined to an angle just sufficient to render the fringes visible. Experiment shows that under these conditions a proportion of polarized light of 1/1000 produces a detectable dissymmetry.

The construction of such an instrument at the California Institute was facilitated by the fact that the nicol prism and the

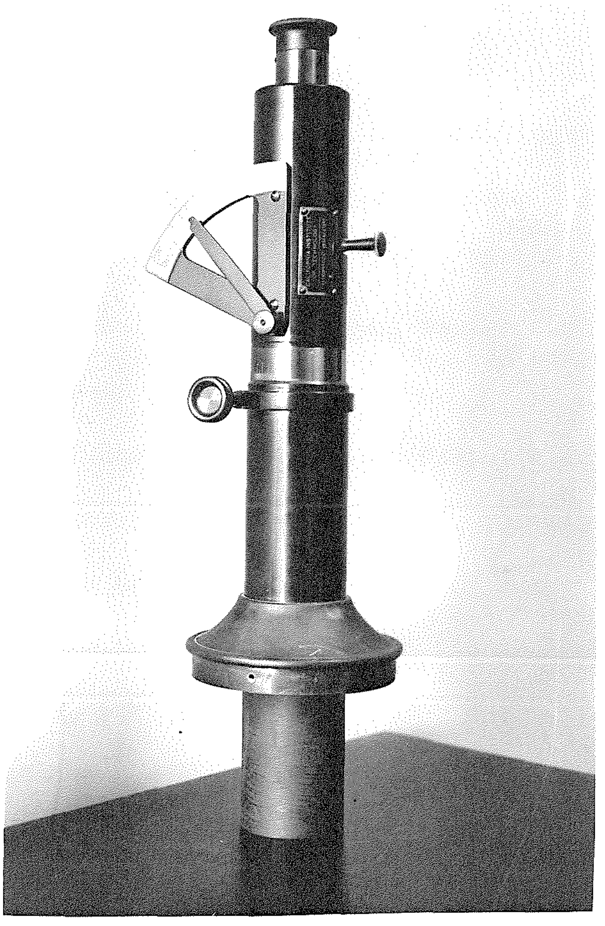

Figure 2

The polarimeter

as constructed at the California Institute lenses for an eyepiece of 1 1/4 inches focal length were already on hand in the Astrophysics Department, while Mr. Babcock, of the Mt. Wilson Observatory, very kindly provided a Savart plate. The mechanical parts were made in the Astrophysics Machine Shop. The plate L_2 was made to be easily removable and was not used at the eclipse, as it was desired to measure, in the two minutes available, as many different points of the corona as possible rather than to secure only one or two measurements of the highest possible accuracy. It is hoped that the same instrument can be used later, with L_2 in place, in the attempt to detect coronal polarization without an eclipse, as mentioned in the introduction.

Some difficulty was encountered in the preparation of the celluloid films for the plates L_1 and L_2. Dr. F. E. Wright, of the Geophysical Laboratory of the Carnegie Institution of Washington, who was working at Mt. Wilson during the fall of 1933 and who had made a Lyot polarimeter of his own, gave some very helpful suggestions as to both the construction and the operation of the instrument. He had made his films according to the simple directions:

> Pour celluloid-amyl acetate solution on good quality plate glass; let dry thoroughly, loosen with water and remove; affix to metal ring with water-glass.[7)]

A number of samples of celluloid were tried, but no success

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7) Recently Dr. Wright has devised a greatly improved technique for preparing celluloid film and has designed some noteworthy modifications of the Lyot polarimeter. See Journal of the Optical Society of America, 24, 206, 1934.

was had in obtaining a clear solution. A gelantinous precipitate was always present which would not settle out in any reasonable length of time. The solution finally used was a commercially prepared lacquer which was perfectly clear. The difficulty of securing films free from waves and wrinkles was met by Dr. Wright's suggestion of affixing the metal ring to the film while the latter was still on the plate glass, then removing the combination from the plate after soaking the whole assembly in water. This procedure required many repeated trials before being carried out successfully, as the soaking process tended to soften the water-glass as well as to loosen the film from the plate.

There still remained the problem of measuring the index of refraction of the film, a quantity required in the reduction of the measured angles of incidence to percentages of polarized light. Using the method of total reflection with a prism spectrometer[8)], it was found that affixing the film to the prism with monobrom napthalene, as recommended, did not secure a sufficiently close contact to give a sharp photometric boundary. The technique finally adopted after considerable experimentation was to evaporate the film directly upon the surface of the prism instead of upon the glass plate; to measure the index of refraction; and then to affix the ring, soak in water, and remove as before. The index of refraction of the film finally used was

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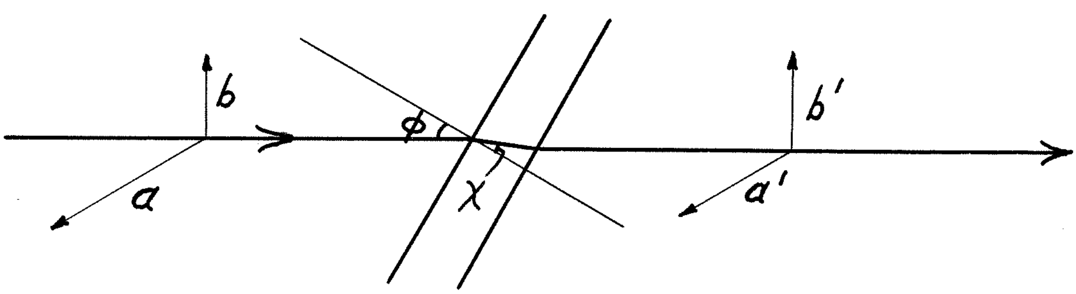
8) R. A. Houstoun, A Treatise on Light, p. 107.

found to be 1.519.

The angle of incidence upon the compensating plate, which is indicated directly upon the sector of the polarimeter, can be made to yield the percentage of polarized light in the incoming beam in accordance with the following considerations. It will be recalled that when the polarimeter is properly oriented, the axis of the compensating plate is in the plane of vibration of the electric vector of the polarized part of the incoming beam. In the accompanying sketch, therefore, the vector a (supposedly perpendicular to the plane of the paper) accounts for all of the plane-polarized light and



for one-half of the ordinary light; the vector b for the remaining one-half of the ordinary light. The fractional polarization is then

$$p = \frac{a^2 - b^2}{a^2 + b^2} \qquad (1)$$

as derived on page 5. The ratio of these components after passing through the plate will be given by[9]

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9) Paul Drude, Theory of Optics, equation (28), p. 285.

$$\frac{a'}{b'} = \frac{a}{b} \cos^2(\phi - \chi) \qquad (2)$$

where χ is the angle of refraction inside the plate. Hence, when the angle of incidence ϕ has been so adjusted as to make $a'/b' = 1$, we have

$$\frac{b}{a} = \cos^2(\phi - \chi) \qquad (3)$$

For any assigned value of ϕ, χ may be computed from the index of refraction (1.519) and the sine relationship. The quantity b/a may be computed from (3), then its square, b^2/a^2, then the reciprocal, a^2/b^2. Since (1) may be rewritten

$$p = \frac{\dfrac{a^2}{b^2} - 1}{\dfrac{a^2}{b^2} + 1}, \qquad (4)$$

the percentage polarization follows immediately. The computation was carried through for five-degree intervals for the range $0^\circ < \phi < 35^\circ$ and for one-degree intervals for the range $35^\circ < \phi < 65^\circ$, the results being summarized in the accompanying curve, figure 3.

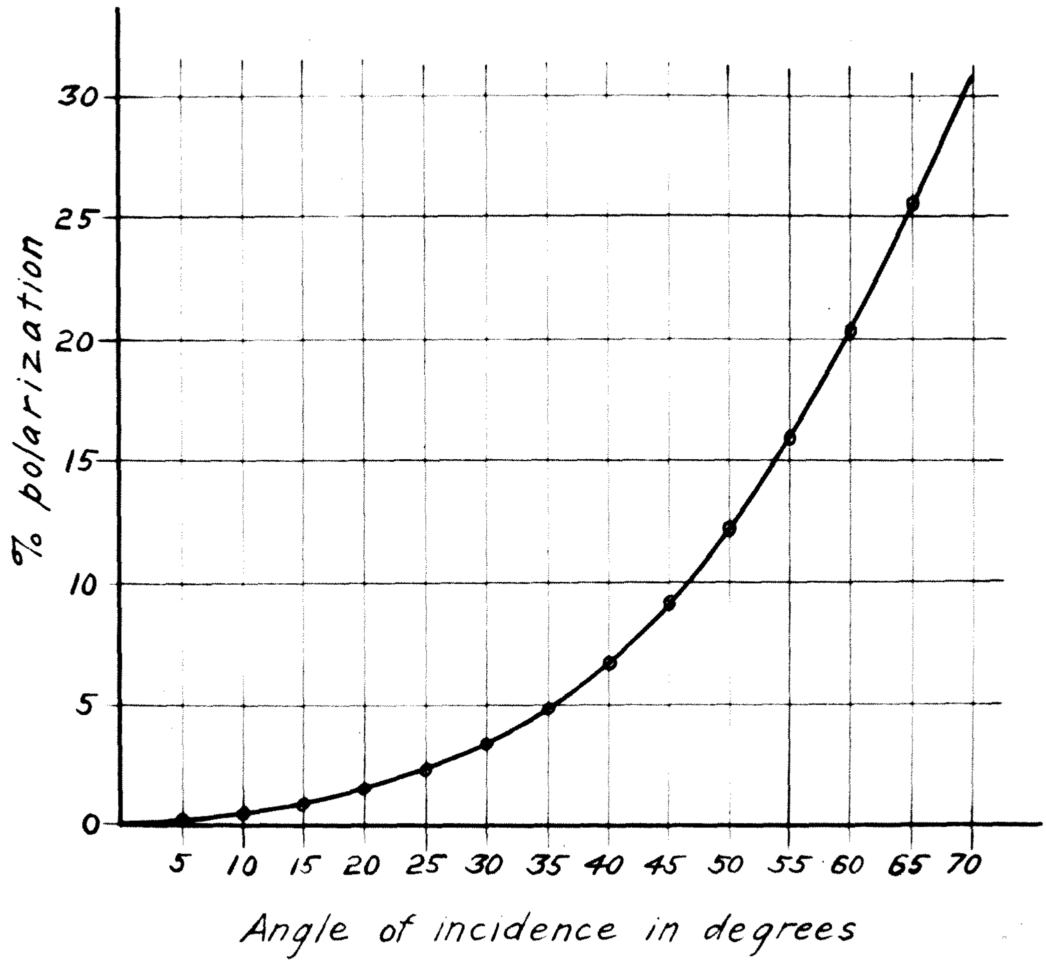


Figure 3

Percentage of polarization

vs.

angle of incidence

II PREPARATIONS FOR THE ECLIPSE

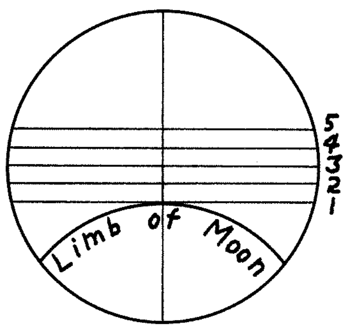
In using the Lyot polarimeter described in the preceding section for measuring the polarization of the solar corona, considerable magnification was necessary in order that distances from the moon's limb might be measured with a fair degree of accuracy. This was attained by attaching the polarimeter in the place of the usual eyepiece of a four-inch refracting telescope. The telescope was supported upon a tripod and hand-driven equatorial mounting (Figure 4) and was readily portable. The finder was provided with a special cap containing a darkened film to facilitate guiding upon the sun in advance of totality.

The instrument was set up on the roof of the Astrophysics Building and test measurements were made of light from the walls of nearby buildings and from selected areas of the sky. These same areas were then measured with Dr. Anderson's polarimeter (pp. 3 - 6). A check of within 1% was consistently obtained. A series of evening observations of the moon demonstrated that it was possible easily to follow the change of polarization with changing phase and that the magnification was sufficient for the isolation of small areas for measurement. At the kind invitation of Dr. Wright, two evenings were spent on Mt. Wilson, where, by means of additional lunar observations, the calibration of the eclipse apparatus was checked against that of Dr. Wright's own equipment.

Figure 4

Four-inch equatorial refractor with polarimeter attached.

A reticle was required to measure distances from the moon's limb out into the corona at eclipse time. Spider web is the traditional material for such devices, but owing to the difficulties of construction and fears of damage in transit or by humid tropical climate, the reticle was prepared by winding fine tungsten wire upon a frame of cardboard and cork. The frame fitted snugly within the tube J (Figure 1) in the focal plane of the eyepiece, which was located slightly below the axis HI. No great success was attained in spacing the wires evenly, but it was possible accurately to measure the intervals.



The lack of a feasible means for illuminating the reticle made the ordinary method of observing star transits impracticable. Observations were made of the moon instead, which rendered all the wires plainly visible. The instrument was so oriented that, with the telescope held stationary, some small detail of the lunar surface would trail accurately along the guiding wire; then the times required to cover the various intervals between the cross wires were measured with a stop watch.

The means of many observations were as follows:[10)]

10) The wire nearest the stem N (Figure 1) was taken as wire #1.

Wire interval	Mean time
1 - 2	8.3 sec.
2 - 3	9.2
3 - 4	10.2
4 - 5	8.7

To evaluate the wire intervals in terms of minutes of arc, we consider first the east-west component only of the moon's apparent motion:

$$1 \text{ second} \cong (15'' - \Delta\alpha)\cos\delta$$

where δ = moon's declination

and $\Delta\alpha$ = change in moon's right ascension

in seconds of arc per second of time. Now at the time of observation, 8 P.M., P. S. T., Oct. 31, 1933, (4h G. C. T., Nov. 1), these quantities had the values:

$$\Delta\alpha = 1^{s}.976 \text{ per min.}$$

$$= 0''.494 \text{ per sec.}$$

$$\delta = +13^{\circ}\ 36'$$

$$1 \text{ sec.} \cong 14''.51 \times 0.972$$

$$= 14''.10$$

$$= 0'.235$$

For the north-south component:

$$\Delta\delta = 13''.1 \text{ per min.}$$

$$= 0''.218 \text{ per sec.}$$

which may be neglected. Multiplying the time intervals by the moon's apparent motion, we have therefore:

Wire interval	Equivalent arc measure
1 - 2	1'.95
2 - 3	2.16
3 - 4	2.39
4 - 5	2.04

A number of test measurements of sky polarization were made after arrival at the observing station in order to make sure that the apparatus was working properly. A practice program involving the manipulation of the polarimeter adjustments while guiding the telescope on the east limb of the sun was carried out on those days which were reasonably clear at eclipse time. At the suggestion of Dr. Willi M. Cohn, a diaphragm was prepared which stopped down the aperture of the telescope from 4 to 1 1/2 inches. This presumably lessened the chance of error due to polarization effects within the instrument. In order to make the best possible use of the two minutes of totality, a plan was devised to obviate the necessity of recording each scale reading as the corresponding setting was made. Tracing paper was pasted over the sector so that the position of the pointer could be marked in with pencil, together with an identifying number. The readings could then be made at leisure. The telescope and polarimeter with the tracing paper in place are shown in Figure 4.

III THE ECLIPSE MEASUREMENTS

A general account of the eclipse expedition is given in an accompanying reprint[11]. Suffice it here to recall that the sky was perfectly clear at eclipse time - a matter of utmost importance for the measurement of polarization. Practice observations of the moon had shown that the thinnest cloud or haze, through which the moon was still plainly visible, caused the percentage polarization to drop to a small fraction of its former value.

Previous results had indicated that the percentage polarization is independent of position angle[12], though this is of course not true of total intensity. It was therefore planned to make measurements at as many different distances from the limb as time permitted, but all in the same position angle. The region selected was that lying directly off the east limb of the sun, as that limb remains visible right up to second contact, thus facilitating the proper pointing of the telescope.

It was possible to have the polarimeter properly oriented in advance, as the polarization is known to be radial[13]; that is, the

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11) J. J. Johnson, "The Japanese Eclipse Expedition of 1934", Popular Astronomy, 42, 307, 1934.

12) N. Ernest Dorsey, "The Polarization of the Corona", Pub. U. S. N. Obs., 4 D, 117, 1905.

13) R. K. Young, "Polarization of the Light in the Solar Corona", Lick Obs. Bulletin, 6, 166, 1911.

so-called "plane of polarization" lies along a radius of the sun; the plane of vibration of the electric vector is tangential. The single wire of the reticle was therefore placed along the sun's east-west diameter, with the #1 cross wire and the axis of the compensating plate tangent to the limb. The cap covering the telescope objective was left in place until a few seconds before totality in order to protect the celluloid film in the polarimeter against overheating.

Beginning immediately at second contact, settings were made upon five different points of the corona, ranging in distance from the limb from 1 to 8.5 minutes of arc. The adjustment required for the disappearance of the fringes was quite definite in each case, so that the results are believed to be accurate to within 1 or 2% of polarization even though the work was carried through as rapidly as possible. The fringes persisted for several seconds after third contact, but the percentage polarization decreased too rapidly to permit quantitative measurement. The settings obtained during totality were as follows:

Distance from limb	Sector reading
$1'.0$	57°
1.9	62
4.1	66
6.5	65
8.5	68

The corresponding percentages of polarization[14] are given in the table, Figure 5.

In the curve, Figure 5, are plotted the values of polarization obtained at several previous eclipses, as well as the 1934 results. Young's values are means of measurements made on a number of plates taken at the eclipses of 1901, 1905, and 1908[13]. Although visual polarimetric observations have been made at many eclipses, Wright[15] and Dorsey[12] are the only observers, so far as the writer is aware, who have committed themselves to a definite percentage polarization at a definite distance from the limb. Wood estimated a polarization of 15 - 20% at the eclipse of 1900[16], a value which tends to fill in the gap between the 1934 results and the 11% obtained by Wright and Dorsey. It seems hard to account for the large discrepancy between 11% and 25 - 28%; although in view of the sensitiveness of polarization to haze and thin cloud mentioned above, it can be explained easily if the earlier eclipses occurred in skies anything less than perfectly clear.

That more visual polarization measurements have not been made at recent eclipses is undoubtedly due to the many advantages of the

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14) J. J. Johnson, Pub. A. S. P., 46, 226, 1934.

15) S. A. Mitchell, Eclipses of the Sun (1932), p. 388.

16) R. W. Wood, Astrophysical Journal, 12, 281, 1900.

Coronal Polarization vs. Distance from Limb

Losap Results

distance from limb	%
1.'0	17
1.9	22
4.1	26
6.5	25
8.5	28

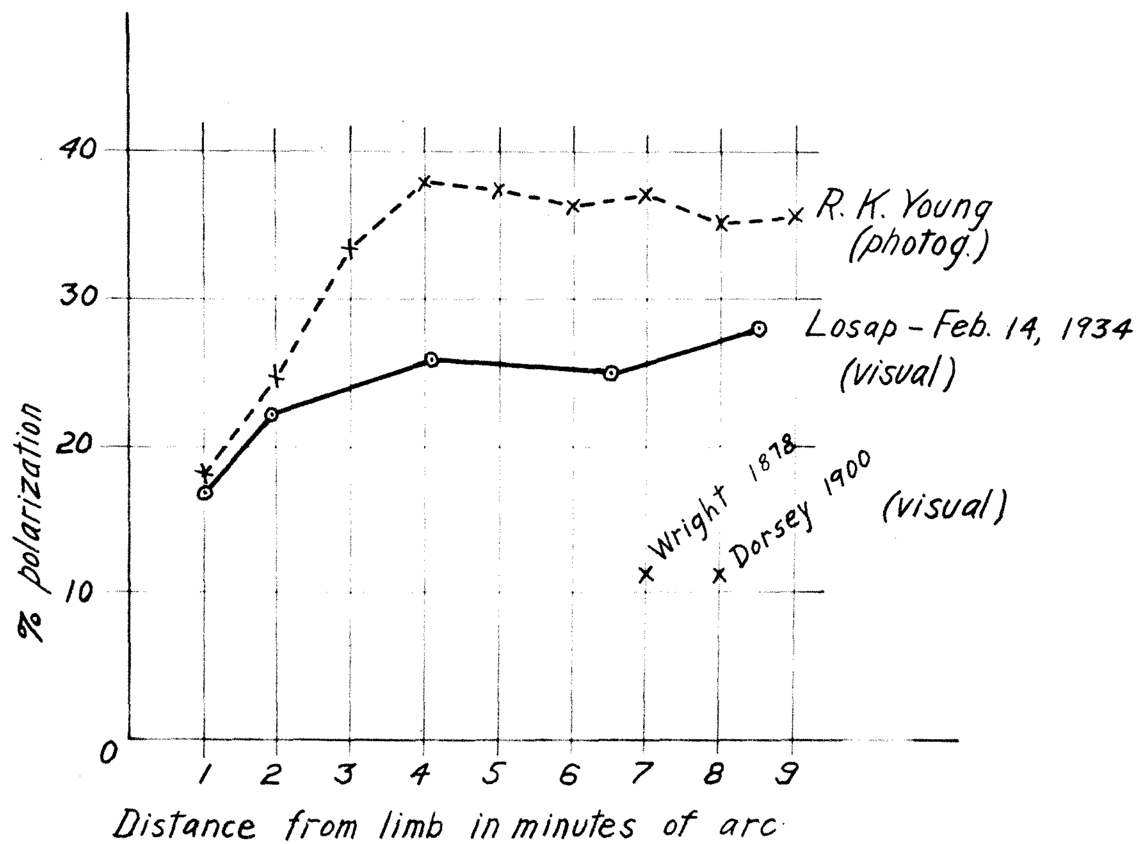

Figure 5 - The eclipse measurements.

photographic methods. But visual observations are still very much in order, owing to the fact that elaborate coronal theories, to be discussed in the following section, have been based upon the supposedly large discrepancy between visual and photographic results.

IV DISCUSSION OF RESULTS

It now becomes in order to consider the various coronal theories which have been proposed, the bearing of polarization measurements upon these theories, and, in particular, the interpretation of the results of the present investigation.

Let it be recalled first of all that the radiation of the corona consists of three parts: a continuous spectrum, the energy distribution of which is practically identical with that of the sun; the emission lines of "coronium", and a Fraunhofer spectrum in the middle and outer corona. We are primarily concerned with the first of these, the continuous spectrum, which comprises over 98% of the total radiation.

Passing over the comparatively crude early theories, which are now mainly of historical interest, we come first upon the idea of Schwarzschild[17)] that the radiation of the corona is due principally to the scattering of light from the photosphere by free electrons. This theory accounted nicely for the white color of the corona, it being assumed that the scattering of light by free electrons is independent of the wave-length. Furthermore, the absence of Fraunhofer lines in the inner corona was accounted for by the necessarily high velocities of the particles of "electron-gas", since the

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17) Astron. Mitteil. d. Sternwarte Göttingen, 13, 63, 1906. Summarized in Handbuch der Astrophysik, IV, 349.

lines would be "smeared out" in accordance with the Doppler principle. One objection to the theory was that it did not accord with the measurements of polarization that had been made up to that time. The differences between the values obtained visually and those obtained photographically (see figure 5) were just about what was to be expected on the basis of Rayleigh's inverse-fourth-power law for the scattering of light by molecules. But this objection loses much of its force if we accept the higher visual values given in this paper. A more serious difficulty is that a corona of pure "electron-gas" would constitute a space charge of inadmissible magnitude. In fact Schwarzschild himself pointed out that the huge negative charge of the electrons would require an equally large induced positive charge on the surface of the sun. This would cause such a strong electrical field that the corona, even if once formed, would immediately collapse.

Ludendorff[18)] overcame this difficulty by assuming that ionized atoms carrying positive charges are mixed with the free electrons.

Minnaert,[19)] accepting the older data on observed polarization, was forced to the conclusion that the hypothesis of free electrons is untenable and that the scattering must be due to bound electrons. To

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18) H. Ludendorff, "Spektralphotometrische Untersuchungen über die Sonnenkorona". Sitzungsberichte der Preussischen Akademie der Wissenschaften, 5, 83, 1925.

19) M. Minnaert, "On the Continuous Spectrum of the Corona and its Polarization". Zeitschrift für Astrophysik, 1, 209, 1930.

explain how the corona could still be white in spite of atomic scattering, he advanced the very ingenious hypothesis that the scattered light is indeed blue, in accordance with Rayleigh's law, but that the emission of the corona itself corresponds to a much lower temperature than that of the sun and is therefore reddish; the two effects just balance.

Recently Grotrian[20)] has offered a suggestion of great interest, though it does not directly concern the subject of our paper, to account for the Fraunhofer spectrum of the outer corona. A cloud of solid or liquid particles, larger than two or three wave-lengths, will reflect all colors equally. Such particles will have low kinetic velocities and will not "smear out" the Fraunhofer lines as would electrons. Grotrian proposed therefore that the outer corona consists of just such particles, necessarily of highly refractory substances. He pointed out that certain carbides and nitrides of titanium and tantalum have melting points around 4000° absolute.

Polarization measurements are of importance in any discussion of coronal theory in that they enable us to distinguish between light from the sun which is scattered by the materials of the corona and light directly emitted by such materials. If light is scattered by

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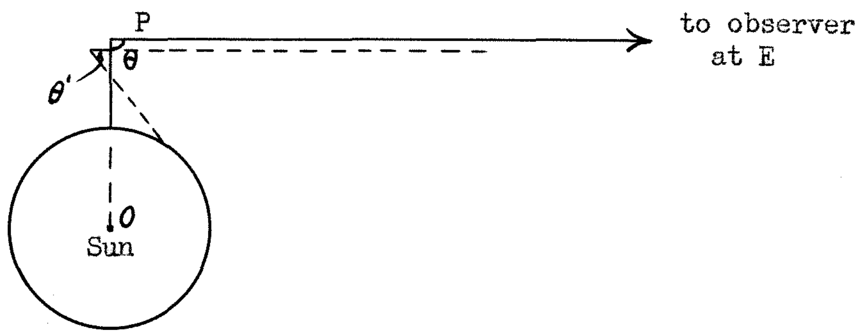
20) W. Grotrian, "Über das Fraunhofersche Spektrum der Sonnenkorona". Zeitschrift für Astrophysik, 8, 124, 1934.

particles, say electrons, which are small as compared to the wave-length, the scattered light will in general be polarized. To a first approximation the light of the corona which we observe at eclipse time has been scattered through an angle (θ in the accompanying diagram) of 90°. For light traveling in the direction OP, the vibrations of



the electric vector will lie in planes perpendicular to OP. The free particle P, acting as a secondary source, will partake of and re-emit these vibrations, which may for convenience be resolved into vibrations in and perpendicular to the plane OPE. Only the latter can be propagated in the direction PE; there is no component of vibration parallel to OP. The observer at E will therefore receive plane-polarized light, the vibrations of which are tangential to the sun. (The "plane of polarization", in the language of the older convention, is radial).

To take into consideration those rays for which θ differs somewhat from 90° (θ' in our diagram), we note that the amplitude A perpendicular to the plane OPE is unchanged, but that there is now a small component in the plane of amplitude A cos θ. This latter may be considered as combining with an equal portion of the perpendicular component to produce ordinary light. The observer will then receive light which is less than 100% polarized. If the particle is self-luminous, the percentage polarization will of course be still further reduced. We thus see that the observed intensity for any particular path is proportional to $1 + \cos^2 \theta$. We shall not enter into a discussion of the factor of proportionality, but simply accept Minnaert's equation[19] for the ratio of the intensity of the light scattered by an electron to that of the incident light:

$$\frac{I}{I_o} = \frac{e^4}{R^2 c^4 m^2} \cdot \frac{1 + \cos^2 \theta}{2} \qquad (5)$$

where e and m are the charge and the mass of an electron, c is the velocity of light, and R is the distance to P from the point on the sun's surface emitting the light. It is to be noted that this equation is independent of wave-length.

To connect the amount of light scattered per unit volume with the observed brightness of a given portion of the corona, a double integration is necessary; the first being with respect to θ for each volume element, the second summing up all the volume elements in the given line of sight. Account may also be taken of the apparent darkening ot the sun's surface near the limb. A number of investigators[21]

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21) Notably Minnaert, Pettit and Nicholson. See footnotes 19 and 23.

have carried through the mathematical analysis. The precise theory becomes important, however, only for points at a small distance from the surface. For distances of several minutes of arc the simple theory is a good approximation. It will suffice for our purpose to bear in mind that the cosine square term in equation (5) will reduce somewhat the expected polarization.

We are now in a position to consider the bearing of our polarization measurements (recall figure 5) upon coronal theory. Previous investigators have assumed, sometimes implicitly, the validity of three postulates. These have already been alluded to in our discussion of the various theories, but, for the sake of clarity, let us tabulate them explicitly as follows:

(1) The observed percentages of polarization are roughly proportional to the percentages of light scattered at the corresponding wave-lengths.

(2) Light is scattered by atoms or molecules according to Rayleigh's law; that is, the scattering is inversely proportional to the fourth power of the wave-length.

(3) The scattering of light by free electrons is independent of the wave-length.

The first of these postulates is dependent upon the fact that not all the light of the corona, even neglecting the "coronium" spectrum, can be due to scattering. For if it were, the percentage of polarization should be much higher. Indeed it should be less than 100% only to the extent required by the cosine square term in equation (5). Furthermore, the percentage of polarization should then be independent of the wave-length even if the intensity varied according to Rayleigh's law. There must be, then, a considerable background of light due to thermal emission or at least to causes other than scattering.[22] If the intensity of the scattered light were small as compared to the intensity of the background, the first postulate would be a correspondingly close approximation. As the ratio is actually about one-third, no more than a rough correlation can be claimed. It is reassuring that the intensity distribution curve for the corona is the same as that for the sun; any discrepancy between them would introduce an added uncertainty.

With regard to the second postulate it is well to note that it was originally derived for "billiard-ball" particles of a certain definite size imbedded in an elastic ether, and may well require modification in the light of present-day theories. It is however believed to be a fair approximation.

The third postulate would appear to be beyond question,[23]

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22) W. Finkelnburg suggests collisions of fast-moving electrons with positive ions. "Cosmic Continuous Spectra and Electron Radiation". Astrophysical Journal, 80, 313, 1934.

23) So far as the visible region of the spectrum is concerned. In the infra-red, scattering by free electrons increases with increasing wave-length. See Edison Pettit and Seth B. Nicholson, "On the Theory of the Continuous Spectrum of the Corona". Astrophysical Journal, 64, 139, 1926.

aside from the entirely negligible reddening due to the Compton effect. In the following discussion we shall assume the validity of the three postulates, but a knowledge of their limitations must restrain us from placing undue confidence in the numerical results.

From these three postulates and the observational data, it is possible to compute the proportion of the light received by the observer which is due to atomic scattering and the proportion due to scattering by electrons. Let P be the percentage polarization measured photographically; V that measured visually. The effective wave-lengths for the two regions are given by Mitchell[24] as 4270 A and 5600 A respectively. Let r be the ratio of these two wave-lengths, 4270/5600. Of the total light received by the observer, let x be the fraction scattered by electrons, 1 - x the fraction scattered by atoms. Then we have

$$V = Px + P(1 - x).r^4$$

whence

$$x = \frac{V - Pr^4}{P(1 - r^4)} \qquad (6)$$

If we put into equation (6) the values of V and P from figure 5 for the distance of, say, 7' from the limb, we obtain x = 0.54; 1 - x = 0.46. It is unlikely, owing to observational uncertainties, that the small fluctuations in the two curves of figure 5 between 4' and 9' have any real significance. We can say only that in the region of the

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24) S. A. Mitchell, "Eclipses of the Sun". Handbuch der Astrophysik, IV, 231.

corona from 4' outward, atoms and free electrons appear to scatter light in approximately equal amounts. For one, two, and three minutes of arc the values of x are found to be 0.92, 0.85, and 0.60 respectively. The first of these values is very doubtful, as at 1' the spread between the visual and photographic curves is so small as to be comparable to the observational uncertainty, which is about 1% of polarization.

In order to apply these results to the problem of the constitution of the corona, it is necessary to know something of the relative "scattering efficiencies" of atoms and electrons. If, for example, light is scattered by an atmosphere consisting of equal numbers of ionized atoms and free electrons (considering various possible gases), what proportion of the total scattering would be due to each?

This is a question which did not confront previous investigators. Accepting the older values for visual polarization, they could say that so far as polarization measurements were concerned, all the scattering seemed to follow Rayleigh's law; even though this was inconsistent with the idea, suggested by other lines of evidence, that much of the scattering is due to free electrons.[25)]

An answer to this question should enable us to determine with some assurance the degree of ionization of the corona in its various parts. If, furthermore, the answer depends upon the kind of atoms

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25) But in a very recent paper J. H. Moore has called attention to the new observations and pointed out that they support Schwarzschild's hypothesis of scattering by free electrons. "The Fraunhofer Spectrum of the Solar Corona". Pub. A. S. P., 46, 298, 1934.

involved, it might even furnish a clue to the chemical composition of the corona.

A priori two viewpoints are possible. One may say that the ionized atom acts as a unit in the process of scattering. It then follows that the free electron has the higher scattering efficiency, for the very existence of Rayleigh's law implies a deficiency on the part of the atom, the deficiency being larger for the longer wave-lengths. Indeed it will be seen that the scattering efficiency is reduced enormously if we replace the mass of an electron by that of an atom in equation (5)[26]. On the other hand, one may say that each bound electron in the atom acts as a unit in the scattering, less effectively perhaps than a free electron, but to such an extent that the aggregate scattering by the atom is much greater, except in the case of hydrogen and possibly helium, than that by a single free electron.

If, as seems likely, this question of scattering efficiencies depends in a critical way upon the physical conditions obtaining in the corona, and since the situation is further complicated by the presence of neutral atoms, no specific conclusions regarding the constitution of the corona are warranted at the present time. But with the accumulation of further data and with the help of the theoretical

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26) This substitution does not give a valid equation for atomic scattering, since no provision is made for the dependence of scattering upon wave-length. It nevertheless illustrates the great difference in order of magnitude between the two cases.

analysis now being undertaken by Dr. P. S. Epstein, it should be possible in the near future to arrive at definite, quantitative results along this line. For the purposes of the present paper we shall content ourselves with the general observation that scattering by free electrons plays an important role in coronal radiation, and with the values derived above for the ratio of the light scattered by electrons to that scattered by atoms.

V CONCLUSION

Visual measurements of the percentage polarization have been obtained for five different points of the solar corona as observed at the eclipse of February 14, 1934. This is believed to be the first time that more than a single point has been measured visually at any one eclipse.

It is highly desirable that more observations be secured, both by the method here described and by some photovisual method employing color filters and suitable plates.[27] It is unfortunate, and in this case unnecessary, that such elaborate coronal theories have been constructed upon such meagre observational data.

Subject to confirmation at a future eclipse, the results of this investigation constitute important evidence in favor of Schwarzschild's suggestion that a large part of the light of the corona is due to the scattering of photospheric light by free electrons.

Values have been derived for the ratio of the light scattered by electrons to that scattered by atoms. A method has been outlined which, if and when properly developed, may well yield important information concerning the constitution of the corona.

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27) Willi M. Cohn secured excellent photographs for this purpose at the 1934 eclipse, but to date has published no results.

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