OBSERVATIONS FROM AN AIRCRAFT OF THE ZODIACAL LIGHT AT SMALL ELONGATIONS

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Summary

The need for polarization data for the zodiacal light between elongations 20° and 35° is discussed. It is shown that such data can be obtained by observations from high altitude, and especially from aircraft, under suitable conditions. Measurements of brightness in absolute units and of polarization obtained between elongations 21° and 31° along the ecliptic using a Sunderland aircraft at a height of 9000 ft over the South Pacific Ocean on 1955 May 24 are given. The zodiacal light axis was then vertical to within 0°.3. The average ecliptic latitude of the axis of symmetry on this occasion was only +0°.17. The data are interpreted in terms of electron densities in interplanetary space, and the effect on the computed electron densities of errors in the data and their interpretation are discussed. The angle between the axis of symmetry of the electron component and the ecliptic for this range of elongation is probably less than 1°.

1. Introduction.—During the last few years there has been a renewed interest in the zodiacal light phenomena, perhaps partly stimulated by a paper of Whipple (1) in which he discusses for the first time the possibility that the phenomena are due entirely to the scattering of solar radiation by free electrons. Since then it has been generally assumed that at least part of the zodiacal light is due to electron scattering, the remainder being due to scattering by dust. The reason for this assumption is that the observed polarization for all elongations smaller than 60° is probably too great to be attributable to dust scattering alone. It is not easy to make a definite decision about this, however, because our knowledge of the dust component is still very scanty, and will not be increased until more observational data are available. Briefly, we may reason as follows. The colour of the zodiacal light differs slightly from that of the average solar disk (2, 3). Hence, not all of the light is due to electron scattering. Further, as the colour is not greatly different from that of the Sun, Rayleigh scattering by dust cannot be the dominant process, and the effective particle size cannot be less than about 0.3μ. This means that the high polarization associated with Rayleigh scattering need not be expected. Van de Hulst (4) has calculated the polarization to be expected from scattering by large particles, obtaining for water droplets scattering through an angle of 30° a value of 5 per cent. The average phase function of zodiacal light particles is not known, but this result makes it likely that the polarization of the dust component is not greater than 10 per cent at elongation 30°. On the other hand, the observed polarization of the zodiacal light at this elongation is of the order of 23 per cent.*

* See paras. 4 and 11 for a more complete discussion.
The important problem has therefore emerged of deducing from zodiacal light data the electron density as a function of distance from the Sun. The general principles involved are well known. The contributions from dust and electrons have first to be separated. The simplest kind of observation that can be used for this purpose is that of polarization. Denoting the brightness of the dust and electron components as $F$ and $K$ respectively, and their polarizations as $p^F$ and $p^K$, we have for the total observed polarization

$$P_0 = \frac{F}{F+K} p^F + \frac{K}{F+K} p^K.$$  

If $p^F$ is known, or can be assumed zero, this equation can be solved by successive approximation and both $K$ and $F$ calculated. For the solar corona, within the range of elongation $0^\circ - 5^\circ$, $p^F$ can without much error be assumed zero (7). But reliable observations of the polarization of the zodiacal light have hitherto existed only for elongations greater than $35^\circ$, and for these elongations we have no knowledge whatsoever of the value of $p^F$. It is true that plausible predictions can be made using idealised models, but for a completely reliable prediction it would be necessary to know accurately the distribution of particles in size, their distribution in space, their shapes and orientations, their surface properties and composition. The supposition of Whipple (6) that the particles are highly porous and of low density complicates the problem even further. There are reasons, even, for supposing that the polarization of the dust component is negative (5). Faced with this problem there are only two courses open to us, if the polarization data are to be used to derive electron densities. We must either measure the polarization of the dust component, or confine work to those elongations where it can be safely neglected. In this paper we consider the second course.

2. Need for observations at small elongations.—In Fig. 1 is shown a curve which gives the maximum likely polarization of the dust component. It has been constructed by taking the kind of value suggested by Whipple (1) and van de Hulst (4) for elongation $60^\circ$, and the values expected for Rayleigh scattering for small elongations, and making a plausible interpolation. The reliability of an electron
density calculation which uses measured values of the polarization at a particular elongation, depends upon the ratio \( R = \frac{p^{F+K}}{p^F} \), \( p^F \) now being the likely value of the dust polarization. The quantity \( R - 1 \) has been plotted in Fig. 2, using the results for \( p^{F+K} \) deduced from observations described later in this paper, and those of Behr and Siedentopf (2), together with the plausible values for \( p^F \) just suggested. No reliance can be placed on electron density deductions at elongations for which \( R - 1 \leq 0 \). This figure demonstrates that, for elongations in the range \( 36^\circ > \epsilon > 22^\circ \), this ratio is never less than 2.7, which means that the error of calculation of electron density, if \( p^F \) is assumed zero, is not likely to be more than 37 per cent. In particular, observations in the region \( \epsilon < 7^\circ \) and around \( \epsilon = 30^\circ \) can be interpreted with a maximum likely error of 30 per cent, while beyond elongation 60° interpretation in terms of electron densities becomes practically worthless (unless there is prior knowledge of \( p^F \)). The minimum elongation for which reliable data for the polarization of the zodiacal light have hitherto been obtained is \( \epsilon = 35^\circ \). The corresponding maximum elongation in the solar corona is 5°. These elongations correspond to minimum distances from the Sun of 20\( R_\odot \) and 123\( R_\odot \), and between these distances there are no electron density values available. It is evidently very important that measures of the zodiacal light should be brought inwards at least to an elongation of about 20°, because this will lead to reliable electron density values being obtained within the distance range 123\( R_\odot \) to 74\( R_\odot \). In this paper we shall show that reliable measures can in fact be obtained at least as close to the Sun as elongation 22°.

![Fig. 2.—Supposed variation of \( p^{F+K}/p^F - 1 \) with elongation (\( p^{F+K} \) is the observed or interpolated polarization of the zodiacal light and \( p^F \) the assumed polarization of the F component).](image)

3. Kind of observations needed.—The prime purpose of these measurements of the zodiacal light would be to obtain reasonably accurate values of electron density. For this, measurements of both total brightness and polarization are required. The more accurate measurements of the brightness of the zodiacal light, for example, those of Roach et al. (3), show that there is a relation of the form \( I = k\epsilon^{-n} \) between the brightness and elongation which represents the observations to a high order of accuracy between elongations 30° and 70°. The aircraft observations of Blackwell (7), which link the solar corona and the zodiacal light,
show that this relation reproduces the observations with an accuracy of the order of 5 per cent at least over the range of elongation $6^\circ - 70^\circ$. As the error in the interpretation of the observations may be as high as 25 per cent there is therefore no need to measure the brightness of the zodiacal light in the very difficult region $20^\circ < \epsilon < 30^\circ$, but it is sufficient to measure it over the range $30^\circ < \epsilon < 50^\circ$ and extrapolate to smaller elongations. It will become apparent later that this simplifies the problem considerably. The polarization, however, presents a completely different problem. As the values which are plotted in Fig. 9 show, it is not possible to make a reliable interpolation between the solar corona and the zodiacal light in the region $20^\circ < \epsilon < 35^\circ$, and it is therefore essential to obtain accurate measurements.

4. Previous observations.—There have been many investigations of zodiacal light brightness. Among the earlier work the most extensive and reliable is that done photoelectrically by Elvey and Roach (8) between elongations $40^\circ$ and $90^\circ$. In work of this kind the great difficulty is to decide upon the brightness of the background, and in a later paper by Roach et al. (6) this problem is discussed in detail. Here, values of zodiacal light brightness between elongations $30^\circ$ and $100^\circ$ are given. The difficulties of measurement are shown by a comparison with the results of Behr and Siedentopf (2); at the elongation of $35^\circ$ the brightness given by Roach is twice that given by Behr and Siedentopf. This may be a real difference in brightness, but Regener (9) in some very careful measurements does not detect any systematic variation with time over a period of 15 months.

There have, unfortunately, been few quantitative investigations of polarization. The first was by Dufay (10) who used a photographic method between elongations $30^\circ$ and $90^\circ$. The second was by Behr and Siedentopf (2) who used a photoelectric method between elongations $35^\circ$ and $90^\circ$. The two sets of data agree as to order of magnitude, but whereas at $40^\circ$ elongation Dufay obtains the value 12.5 per cent, Behr and Siedentopf derive 23 per cent. Take-uchi (11) has made measurements at elongation $60^\circ$. No observations exist for the important range of elongation $20^\circ < \epsilon < 35^\circ$.

5. Conditions for observations in this region.—To observe the zodiacal light at small elongations it is clearly necessary to observe as soon after sunset and as close to the horizon as possible. Suppose that under exceptional conditions it is possible to observe within $4^\circ$ of the horizon. Fig. 3 shows the brightness of the zodiacal light and of the sky that may be expected at altitude $4^\circ$ for different depressions of the Sun below the horizon. The zodiacal light curve shows the observed brightness uncorrected for atmospheric extinction. The data for the sky brightness in this figure, which are approximate only, have been obtained photographically from an aircraft by methods described later. Some ground observations at smaller depressions of the Sun below the horizon have also been used in constructing the diagram, all of which refers to an effective wave-length of 6300 A.

The diagram demonstrates that under these conditions the zodiacal light is equal in brightness to the sky background at an elongation of $23^\circ$. If the atmospheric conditions are satisfactory it should thus be possible to make observations to at least this elongation. However, the sky brightness increases very rapidly with decreasing depression of the Sun below the horizon and it is clear, first, that good timing of the observations is necessary, and secondly, that the smallest elongation at which observations can be made is sharply defined.
The second intersection of the two curves at elongation 29° is of no significance because there is no need to observe at this elongation so close to the horizon.

![Variation of sky brightness and zodiacal light brightness with depression of the Sun below the horizon. All measurements refer to an altitude of 4°.](image)

It is clearly essential to have exceptionally good observing conditions for quantitative observations of this nature. In particular, it is not easy to make such observations from the ground because the light path passes very close to the Earth's surface for a great distance, and is therefore much influenced by low lying dust and haze. To avoid this difficulty it is desirable to observe over a sea horizon either from an isolated mountain peak or from an aircraft. The great advantage of an aircraft is that it enables observation to be made over open ocean, far from large land masses, where the air is virtually free from dust and smoke. Under these conditions the atmospheric extinction is small (as is demonstrated later) and its variation with altitude regular. From an elevated position useful observations can be made down to an altitude \( \phi \) above the depressed horizon, where \( \phi \) is the depression of the horizon. In this problem there is little to be gained from observing at a height* greater than 10 000 ft; at this height the observer is already above most haze and dust, and observations can be made to within 2° of the horizon before the haze layer is penetrated by the light path.

To reduce as much as possible the effects of atmospheric extinction the ecliptic should be nearly vertical.

6. Observations.—The observations of the zodiacal light described here were made as part of the programme of an expedition to Fiji to observe the total solar eclipse of 1955 June 20. These observations were planned to be complementary to the eclipse observations, all being made at about the same time. They were made over sea in an open Sunderland aircraft of the Royal New Zealand Air Force at a height of 9000 ft and in the approximate position

\[
\begin{align*}
\text{Latitude} & \quad 16°3\ S \\
\text{Longitude} & \quad 179°5\ W
\end{align*}
\]

* In this paper the following usage is adopted: height refers to elevation of aircraft above ground, altitude refers to angular elevation of line of sight above horizon.
Two flights were made for this purpose, both in excellent weather conditions. No photographs were taken near sunset because of the confusion at that season between the Milky Way and the zodiacal light.

Table I

<table>
<thead>
<tr>
<th>Date</th>
<th>Photograph</th>
<th>Inclination of ecliptic to vertical</th>
<th>Mean depression of Sun below horizon</th>
<th>Mean galactic latitude</th>
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<tr>
<td>1955 May 24</td>
<td>I</td>
<td>0° 19'</td>
<td>19° 7</td>
<td>-50°</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>9° 32'</td>
<td>18° 1</td>
<td></td>
</tr>
<tr>
<td>1955 June 24</td>
<td>III</td>
<td></td>
<td>19° 3</td>
<td>-25°</td>
</tr>
<tr>
<td></td>
<td>IV</td>
<td></td>
<td>17° 2</td>
<td></td>
</tr>
</tbody>
</table>

![Graph showing spectral sensitivity](image)

*Fig. 4.—Spectral sensitivity of camera for sources of colour temperature 6000 deg. K and 1490 deg. K.*

The camera was similar in design to that used to observe the total solar eclipse of 1954 June 30; a description of this camera has already been published (7). There is no need in work of this kind to use high quality lenses; we are simply measuring the brightness of a featureless surface, and in any case without elaborate apparatus the irregular motion of the aircraft during the relatively long exposures soon vitiates good definition. Three simple lenses of white glass were used, each of diameter 7.1 cm and focal length 12.9 cm, with relative aperture f/1.8, giving a plate scale of 0°.44 per mm and a field of 60°. Each lens was used in conjunction with a Chance OY1 filter, giving the spectral sensitivity shown in Fig. 4 for a source at 6000 deg. K. The effective wave-length* is close

* The evaluation of the effective wave-length is described in detail in a previous paper (5).
to 6300 Å. Two of the three lenses were also backed by suitably orientated sheets of HN22 Polaroid filter. The three lenses formed three separate images on to one Ilford HP3 plate. Under these conditions an exposure of 5 min gave an excellent direct photograph, but an underexposed polarization photograph. Photographs I and II were given exposures of 15 min and 5 min respectively, and III and IV were given 8 min and 4 min. Nos. I and II were taken while the zodiacal light was still almost uncontaminated by sunlit sky near the horizon, III and IV were taken later to obtain the polarization of the dawn sky.

Several hours later on the ground an absolute calibration from a sub-standard lamp was put on to another plate of the same batch through a quartz step wedge, and the zodiacal light plate and calibration plate developed together. The substandard lamp was later compared with a second standard which had been calibrated by the National Physical Laboratory. The brightness of the zodiacal light could thus be obtained in absolute units, and by using the value for the mean brightness of the Sun given by Minnaert (12) the zodiacal light could be related directly to the average brightness of the solar disk. Precautions mentioned in a previous paper (7) were taken to ensure photometric accuracy. Particular attention has been paid to the variation of camera sensitivity with distance from the optical axis.

The camera was mounted on a table behind an open hatch in the side of the aircraft. A crude attempt to guide was made, but much reliance was placed on the stability of the aircraft. It was found that in reasonably good flying conditions this results in nearly round star images rather more than 1° in diameter for an exposure time of 5 min. Such definition is amply good enough for this problem.

7. Measurement of atmospheric transmission.—The atmospheric transmission was measured on one occasion only from the aircraft at a height of 9000 ft, but as the sky was of excellent quality on this occasion, and on all other occasions when observations were made from the aircraft, the results can be assumed to be representative. The extinction was measured by taking calibrated photographs of the rising moon. In the reduction of the observations the extinction formula

$$I = I_0 e^{-km_0}$$

was used, where $I_0$ is the intensity of radiation entering the Earth's atmosphere, $I$ the observed intensity, $k$ an absorption coefficient and $m_0$ the total mass of air along the line of sight. The unit of $m_0$ is the mass of air along a vertical line of sight starting from the Earth's surface. The quantity $m_0$ has been evaluated by numerical integration for an aircraft height of 9000 ft and for various altitudes above the horizon, using a standard atmosphere (13). A plot of $\log I$ against $m_0$ now gives the value of $k$. A good fit to a straight line was obtained for values of $m_0$ ranging from 9.5 air masses to 20.8 air masses, the gradient of which gives the value $k = 0.080 \pm 0.01$ air mass$^{-1}$.

A comparison of this value with those values given by Allen (14) for the various atmospheric constituents demonstrates the almost complete absence of atmospheric dust during the present series of observations. At this geographical position the contributions to $k$ given by Allen are, excluding dust,

- from molecular scattering: 0.0558
- 1 cm precipitable water (p. 110, 111): 0.0018
- 2 mm ozone at N.T.P. (p. 120): 0.0193
Making a total of $k = 0.077$. This means that the contribution from dust is between $0.003$ and $0.013$. For “fairly clear conditions” Allen gives the dust contributions as $k = 0.055$, which is about seven times greater than the value found in the present work.

We are forced by the nature of the problem to work as close to the horizon as possible, so that we should now ask the question—how accurately should the extinction be measured? It is seen from equation (2) that the error $\Delta I_0$ in deriving the true intensity $I_0$ from a measured intensity $I$ is related to the error $\Delta k$ in measurement of $k$, by the relation

$$\frac{\Delta I_0}{I_0} = \frac{\Delta k}{k} \cdot \log_e \frac{I_0}{I}.$$  

The ratio $\left[ \frac{\Delta I_0}{I_0} \right] / \left[ \frac{\Delta k}{k} \right]$ is plotted against altitude in Fig. 5 for $k = 0.080$ air mass$^{-1}$, and a height of 9000 ft. The probable error in $k$ is of the order of 10 per cent, and from the diagram we deduce that at all altitudes greater than $4^\circ$ above the depressed horizon the error in derivation of $I_0$ from this cause is less than 10 per cent. At $10^\circ$ above the horizon it is only 3 per cent. These errors are much smaller than those due to uncertainty in the sky background, and it is therefore sufficient to know $k$ to within 10 per cent. We emphasize again at this stage, that it is possible to treat atmospheric absorption quantitatively at such low altitudes only because of the absence of dust or smoke haze along the line of sight, due partly to the geographical positions and partly to the use of an aircraft.

These absorption coefficients refer to a point source outside the Earth’s atmosphere. It is the usual practice in investigations of the night sky light to use a value for the extinction which is one half of this (15, 16). This procedure is used because the absorption is chiefly due to scattering and in any direction the observer sees light scattered from all parts of the night sky. In this case it is not justified because the solid angle subtended by the zodiacal light is comparatively small, and the point source extinction is used.
8. Measurement of position on the photographs.—As the photographs show stars to the fifth magnitude, there are sufficient data for a plate solution by a modification of Turner's method (17) in which the plate distortion of the optical system is first measured. The positions of the star images on the better plates can be measured with a ruler to within 0.2 mm or 0.1°, and the first plate solution reproduces their positions with this accuracy. The average position of the horizon is reasonably well defined and the altitude of any part of the sky above the horizon is taken directly from the photograph. There is thus no need to have any knowledge of the position or orientation of the aircraft, or of the precise time at which the photograph was taken.

9. Axis of symmetry of zodiacal light.—The first two plates are well suited to this measurement because when they were taken the ecliptic was vertical at the horizon to within a fraction of a degree. These photographs were taken with the Sun at the average distance of 19°.7 and 18°.1 below the horizon respectively. Table II gives the deviation of the axis of symmetry of the zodiacal light from the ecliptic, averaged from these two plates. All deviations are to the north of the ecliptic. The accuracy of measurement is of the order of 0.1°. The average deviation on this occasion was only +0.17, which in circular measure about the Sun is 0.28°. These results support the view of Regener (9) that the zodiacal light is indeed highly symmetrical with respect to the ecliptic. Presumably the axis of symmetry tends towards the solar equator with decreasing distance from the Sun. However, the change from the ecliptic to the solar equator must occur comparatively close to the Sun because, on this occasion, the angle between the two was 7°.1.

10. The brightness of the zodiacal light and of the sky background.—Our task is to measure the brightness of the zodiacal light as a function of distance from the Sun as far as elongation 50°. For this purpose plate I has been used because this was the earliest photograph of the series and was taken when the Sun was so far below the horizon that, except for a band very close to the horizon, none of the sky background brightness is due to the scattering of sunlight in the Earth's atmosphere. Visual examination of the appearance of the dawn sky makes it clear that the scattering of sunlight is at first confined to a narrow band at the horizon, for it is here that the sky suddenly begins to brighten, the part above remaining dark for a longer time. The brightness has been measured by scanning the plates with the Cambridge Observatories microphotometer. The procedure outlined by Roach et al. (3) has been used to obtain the sky background down to elongation 28°. The resulting data obtained from plate I are shown in Fig. 6. It should be emphasised at this stage that aircraft observations are not necessarily more accurate than ground observations for elongations greater than 35°. The barrier to high accuracy in this region is the brightness of the inevitable background,
and if the Sun is $20^\circ$ below the horizon this is not appreciably diminished by observing from an aircraft. These observations are not in good agreement with those of Roach et al. (3). For example, at elongation $35^\circ$ we obtain a brightness of $3.89 \times 10^{-13} B_\odot$, where $B_\odot$ is the average brightness of the solar disk at $\lambda 6300$ A. Roach* obtained the value, on 1952 November 18/19, of $5.15 \times 10^{-13} B_\odot$. Regener, in his careful work, obtained $7.29 \times 10^{-13} B_\odot$, using a photoelectric cell without a colour filter. Behr and Siedentopf (2), on the other hand, at wave-length $5400$ A, obtained the value of $3.46 \times 10^{-13} B_\odot$. It is important to decide whether these discrepancies represent a real variation or are the result of errors of observation. The following points are relevant to this matter. First, it is most undesirable to use stars of known stellar magnitude as an intermediate standard of surface brightness. The surface brightness of the zodiacal light has eventually to be related to the surface brightness of the Sun, and the extinction produced by the Earth’s atmosphere enters once into all reductions. A more direct and satisfactory procedure is therefore to measure the brightness of the zodiacal light in absolute units and to make a good estimate of the atmospheric extinction at the time of observation. The atmospheric absorption from a height of $9000$ ft and at an altitude of $15^\circ$ above the horizon (corresponding to an elongation of $35^\circ$) is of the order of $20$ per cent at wave-length $6300$ A under good conditions; it should be possible to determine the extinction coefficient with an error of less than $10$ per cent, and hence the error in the extra-terrestrial flux from this cause should be less than $2$ per cent. Second, the error in measurement of brightness at elongation $35^\circ$ due to an error in the estimation of the background is small. At this elongation, according to these measurements, the contribution of the zodiacal light is about $67$ per cent of the total, and even if the estimate of the background light is $50$ per cent in error, the error in the zodiacal light measurement will be only $24$ per cent. The discrepancies noted above are much larger than this; in the present work even the sum of zodiacal light and background is still not equal to the zodiacal light brightness observed by Roach; the extreme variation in the values given by Roach is $49$ per cent. In spite of the comments

* The value for $6300$ A is considerably lower than the mean value for all wave-lengths.
of Regener, it is difficult to believe that the observed variations are other than real. Thirdly, as the zodiacal light is due to the scattering of sunlight, its brightness should be referred to that of the average Sun and not that of the centre of the disk. In particular, the colour of the zodiacal light should be compared with the colour on the average solar disk.

**Fig. 7.**—Observed brightness of zodiacal light (uncorrected for extinction) and brightness of sky background for a depression of the Sun below the horizon of 19°.7.

**Fig. 8.**—Observed brightness of zodiacal light (uncorrected for extinction) and brightness of sky background for a depression of the Sun below the horizon of 18°.1.
The data for the brightness of the zodiacal light obtained from plate I can now be applied to plate II, taken a few minutes afterwards, to find the increased contribution of the sky brightness from scattered sunlight. The results are shown in Figs. 7 and 8 for two depressions of the Sun below the horizon. Each of these diagrams gives data for various altitudes above the horizon for one position of the Sun below the horizon; in Fig. 3 the data relate to one altitude of observation and a range of positions of the Sun. All the diagrams show that observations of this nature near the horizon cannot be made with the Sun less than about 18° below the horizon. This is an absolute limit to observation by this method, which will not be appreciably improved upon by observing from a greater height.

11. Measurement of polarization.—The polarization photographs on plate II are of good quality and better exposed than those on other plates; only these photographs have therefore been used in the reductions.

The observed polarization is the sum of contributions from the zodiacal light, scattered sunlight and night sky background. If \( P_0 \) is the observed polarization, we have

\[
(I_Z + I_S + I_N)P_0 = I_Z P_Z + I_S P_S + I_N P_N
\]

where \( I_Z, I_S \) and \( I_N \) are the intensities of the three components, and \( P_Z, P_S, P_N \) their polarizations. To obtain \( P_Z \) from the observed polarization it is necessary to know \( I_Z, I_S, I_N, P_S, P_N \).

The separation of the observed intensity into the two parts \( I_Z \) and \( I_S + I_N \) has already been discussed. A careful separation of \( I_S \) and \( I_N \) is not required because under these conditions the contribution from scattered sunlight, \( I_S \), both in intensity and polarization, is far greater than that from the night sky. An approximate value for \( I_N \) has been taken from plate I.

Scattered sunlight predominates in the photographs on plate IV, and this plate has been used for the measurement of its polarization. At an altitude of 7°5 above the depressed horizon the observed polarization is 10.0 per cent. Putting in a correction for the zodiacal light contribution, this gives the value of 9.2 per cent for the polarization of the sunlit background. This is close to the value of 9.6 per cent, which would be predicted by a simple application of Rayleigh scattering theory at this elongation. The values of \( P_S \) for various altitudes above the horizon have therefore been computed from this theory. This is preferable to a direct measurement because at higher altitudes there is an increasing confusion with the zodiacal light and at lower altitudes the photographic density becomes too high for accurate measurement.

The value chosen for \( P_N \) is not critical. Van de Hulst (18) has pointed out that the night sky background should be polarized very near the horizon because here it is chiefly scattered light that is seen. Following the computations of van de Hulst we have taken the polarization of the sky emission to be 6 per cent at the horizon, diminishing to 1 per cent 10° above the horizon.

The observed polarizations on plate II vary from 7 per cent at elongation 20° to 15 per cent at elongation 30°. The data resulting from the reduction of the smoothed observations are shown in Fig. 9. Also on Fig. 9 are plotted the data from the 1954 eclipse (5, 7) and those taken from the work of Behr and Siedentopf (2). The present results appear to confirm the high polarizations obtained by Behr and Siedentopf, but do not agree with the smaller polarizations found
of the zodiacal light at small elongations

by Dufay* (10). It is unfortunate that insufficient exposure prevents the present observations being continued beyond elongation 30°, because a combination of these data with those of Behr and Siedentopf makes it likely that there is a maximum of polarization near elongation 35°.

Fig. 9.—Polarization of outer corona and zodiacal light. Data for the outer zodiacal light are from the work of Behr and Siedentopf.

A potent source of error in all measurements near the horizon under these conditions can result from near specular reflection from the sea. At an angle of incidence of 84° the reflection coefficient is about 52 per cent and the degree of polarization of the reflected light is 18 per cent. Serious errors will result if any of this light intrudes upon the zodiacal light. This will occur if the guiding (which results in sharp star images and a blurred horizon) or the lens aberrations cause some mixing. To avoid the effects of diurnal motion it is not sufficient to guide well; it is also necessary to use a short exposure to give a sharp horizon. The data presented here are probably not seriously affected by errors of this kind.

* Dufay makes no mention of his correction for the sky background; his observations may be undercorrected.

<table>
<thead>
<tr>
<th>Elongation</th>
<th>Polarization</th>
</tr>
</thead>
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<tr>
<td>5°</td>
<td>2.8 per cent</td>
</tr>
<tr>
<td>10°</td>
<td>3.7</td>
</tr>
<tr>
<td>20°</td>
<td>9.5</td>
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<tr>
<td>25°</td>
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<tr>
<td>50°</td>
<td>21.7</td>
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The error of these measurements is unlikely to be greater than $\pm 3$ per cent in absolute measure, i.e., the maximum relative error varies from $\pm 30$ per cent at $22^\circ$ elongation to $\pm 15$ per cent at $30^\circ$ elongation.

It is now possible to interpolate the polarization measurements between the solar corona and the zodiacal light. Table III contains polarization data for a smoothed model between elongations $5^\circ$ and $50^\circ$, which is based partly on Behr and Siedentopf's data, and is partly an interpolation between the outer corona and the inner zodiacal light.

The polarization data of Fig. 9 and the intensity data of Fig. 6 have been used to calculate electron densities in the zodiacal light region along the ecliptic assuming that the polarization of the $F$ component is zero for the range of elongation $5^\circ$ to $50^\circ$. The results are shown plotted in Fig. 10 (middle line) together with data previously obtained on the outer corona. These values are lower than those given in a previous publication (2) because the smaller values for the brightness of the zodiacal light found in the present paper have been used.

At large elongations ($\epsilon > 50^\circ$) considerable errors in electron density values can result from the assumption $p^F = 0$. Maximum and minimum values of electron density have been computed using the data of Fig. 1 for the maximum likely polarization of the $F$ component (positive or negative). No account has been taken of the possibility of a sudden cut-off of electron density. The results are shown in Fig. 10 as the upper and lower curves. These curves also include the effects of an uncertainty in the brightness of the zodiacal light of 20 per cent, and an uncertainty in the polarization at elongation $30^\circ$ of $\pm 2$ per cent absolute.

It is important to know how symmetrical about the ecliptic is the electron component. The likely deviation from the ecliptic can be determined from these...
observations only if the shape of the electron cloud is known. To form an order of magnitude of the quantities involved we assume that the electron cloud is an ellipsoid of revolution with major and minor axes in the ratio of 5:1—a not improbable value judging from the electron density data obtained at the 1954 eclipse (5, 7). Knowing, now, the contribution of the electrons to the total zodiacal light, and also the fact that the axis of the total light is within 0°.3 of the ecliptic (in circular measure about the Sun), we can calculate the maximum likely deviation of the axis of the electron component from the ecliptic. The result is that the axis of symmetry of the electron component is probably not more than about 1° (in circular measure) from the ecliptic.

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