PRECISE DETERMINATION OF THE ORIENTATION OF THE PLANE OF POLARIZATION IN THE SOLAR CORONA

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Abstract. It has been shown by Molodensky (1973), that precise measurements of the position of the plane of polarization in the corona may allow us to observe overthermal electrons in the solar corona. For such measurements during the eclipse of 10 July 1972, a method based on the photographic recordings of the corona by means of a cineset and with an automatically rotating polaroid has been developed. A technique has also been developed for determining the position of the plane of polarization by means of isophotes obtained with polarization filters. This technique uses the photometric data for determining phase shifts between the apparent intensity variation curve and a similar curve expressing the rotation phase of the polaroid. The results of the measurements for $h/R_{\odot}=0.5$ to 0.9 allow us to conclude that:

(1) The plane of polarization (E-vector position) coincides very exactly with the tangential direction in the region of N-W limb. The maximum deviations of this plane amounts to 1–1.5°, and the mean-square deviations in this region amount to $\sim 0{,}3°$ at $h/R_{\odot} \approx 1$. This coronal region was the least active one and there were no spots there.

(2) The corona near the E limb consisted of two 'fans' divided by a thin beam. In that region some deviations of the plane of polarizarion from the tangential direction were revealed. Those deviations were of the order of 3°. During the time of the eclipse there were some groups of spots behind the E limb (but close to this limb). The observed deviations were apparently connected with those groups.

(3) Calculations have been made of the turn of the plane of polarization caused by an inhomogeneity in the radiation field from the photosphere and due to the presence of spots. The effect qualitatively coincided with that shown by the measurements.

1. Introduction

Most routine observations for studying the polarization of the white corona are made by taking several photographs of the corona with different orientation of the polaroid. To determine the three characteristics of the linearly polarized light (the intensities of both non-polarized and polarized components and the polarization direction) it is necessary and sufficient to have three photographs in polarized light. The errors in the determination of the polarization direction are usually 7–10° (Klüber, 1958; Vashakydze, 1949; Sazanov, 1972; Saito, 1970). But some authors have obtained deviations 2 to 3 times greater (Fracassini and Hach, 1963; Koutchmy and Schatten, 1971). If these deviations are real, this may indicate that in some regions of the corona we observe the electrons with energies ~ 10 keV (Molodensky, 1973). The principal problem is to improve the precision of polarization observations.

2. The Observational Technique

To observe the eclipse of 10 July 1972 (Chukotka, the cape 'Russkaya Koshka') the following set was constructed.

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At a parallactic mounting the cine-camera was installed (with the objective $F=1$ m, $d=10$ cm and with a filter placed in front of the film at a distance of 20 mm). The filter was made of two standard color filters ($\lambda > 5000$ Å) between which a polaroid film had been cemented.

The filter was placed in a frame mechanically connected with a 'greifer' mechanism of the cine-camera in such a way that the film was being rewound when the polaroid was turned by 7.5°. Exposures and rewinding of the film were performed automatically. Exposures were 0.203 sec and was kept constant with that accuracy with which the frequency remained constant in the electric circuit (according to the data without eclipse, the fluctuations did not exceed 1%). The time of rewinding was 0.04 sec. Isopanchromatic film ($\lambda < 7000$ Å) and Kodak developer D-19 ($\gamma = 2$) were used.

During the total phase (106 sec) 430 frames of film (18 × 24 mm) were taken, and the polaroid made 10 full rotations during that time. After the total phase solar disk images were taken through a polaroid but with neutral filters mounted in front of the objective. From these frames the determination of the precision of one of the methods of measurements was performed. The material was analysed by means of two independent methods as described in the next sections.

3. The Isophotes in Polarized Light

The film was copied in duplicates by means of an automatic copying device using various exposures and a high contrast photomaterial (contrast coefficient $\gamma = 4.5$). To receive sharp isophotes, 3 successive copies were made, so the total contrast coefficient (with the account of original) was ~ 15.5. The images showing in this way the isophotes were projected in large magnification on a screen and then drawn. The most careful attention was given to the accurate combination of individual frames. As a result the accuracy of the combination proved to be as good as 10″ or even better. Of the same order of magnitude were the errors in the drawing of isophotes. These isophotes allowed us to determine the position of the polarization plane in corona. The method used by us is based on the following consideration:

Let f_0 and f_p be the intensities of a non-polarized and a polarized component of the corona radiation, θ the angle between the direction tangential to limb and a selected standard direction, and $\Delta(r, \theta)$ the angle of deviation of the polarization plane from tangential direction. Then the intensities of the radiation transmitted through the polaroid oriented under the angle φ to the standard direction, is described by the function

$$I_\varphi(r, \theta) = \tfrac{1}{2} f_0(r, \theta) + f_p(r, \theta) \cos^2[\theta + \Delta(r, \theta) - \varphi]. \tag{1}$$

The isophotes obtained when turning the polaroid (by 7.5°) give a family of curves

$$I_{\varphi_i}(r, \theta) = c, \tag{2}$$

where $i = 1, 2, \ldots, 24$, and c is a certain constant.

Let us analyse some features of these curves.

1. Consider the envelope of this family. If we differentiate (2) by φ_i, we get

$$f_p \sin 2(\theta + \Delta - \varphi) = 0. \tag{3}$$

It follows from (1) and (3) that the family (2) has two envelopes:

$$\begin{aligned} \tfrac{1}{2} f_0 + f_p &= c, \\ \tfrac{1}{2} f_0 &= c. \end{aligned} \tag{4}$$

With $\Delta \ll 1$ the first curve corresponds to the isophote obtained with a radial polaroid which transmits polarized radiation, and the second curve with one which stops it. All isophotes of the family (2) are located inside the ring limited by curves (4).

2. Consider a pair of curves corresponding to various positions of polaroid φ_i and φ_k. The points of their crossing are determined by the solution of the system of equations:

$$\begin{aligned} f_0 + f_p + f_p \cos 2(\theta + \Delta - \varphi_i) &= 2c, \\ f_0 + f_p + f_p \cos 2(\theta + \Delta - \varphi_k) &= 2c. \end{aligned} \tag{5}$$

Subtracting the second equation from the first one we have:

$$\cos 2(\theta + \Delta - \varphi_i) = \cos 2(\theta + \Delta - \varphi_k), \tag{6}$$

i.e. $\theta + \Delta - \varphi_i = \pm (\theta + \Delta - \varphi_k) + n\pi$.

Then we shall have:

(1) $\varphi_k - \varphi_i = n\pi$

giving a trivial solution which must be rejected, and

(2) $2(\theta + \Delta) = \varphi_i - \varphi_k + n\pi$

or

$$\theta = -\Delta(r, \theta) + \tfrac{1}{2}(\varphi_i - \varphi_k) + n\pi/2. \tag{7}$$

It is seen from the obtained expression that with $\Delta = 0$ any two isophotes are crossed in 4 points; they are at the distance $\pi/2$ from each other, i.e. two straight lines connecting the points $n = 2;\ 4$ and $n = 1;\ 3$ are perpendicular. Their intersection coincides with the center of the Sun because with $\Delta = 0$ the polarization is geometrically connected with this centre.

It is not difficult to understand this requirement. Really, the radiation from the corona consists of non-polarized and polarized components. The polaroid transmits the non-polarized component with the same intensity independently of orientation. As for the polarized component, we find that for two positions of the polaroid the intensities are equal at the bisectors of the angles formed by the vibrational direction and the polaroids transmission. The two bisectors obtained in this way are crossed at the right angles. In case of a deviation of the vibrational direction from the tangential direction the picture is disturbed. In fact we find from expression (7)

$$\Delta(r, \theta) = -\theta + \tfrac{1}{2}(\varphi_i - \varphi_k) + n\pi/2, \tag{8}$$

where θ is the experimentally obtained 'angles of crossing'.

Thus, the intersections of the isophotes give the 'coordinate net' in the region between two envelopes (4). As is seen from (7) the radius-vector drawn from the solar centre to any point of crossing gives successively those points of corona in which the real position of polarization differs from the neighbouring ones by 7.5°.

To determine Δ by formula (8) the most suitable are obviously the isophotes strongly differing from each other (i.e. those obtained at $\varphi_i - \varphi_k \approx \pi/2$) because they intersect under the largest angles and errors in the isophotes themselves will be of minor influence on the determination of points of crossing.

Note that if the difference i–k in expression (7) is even, then with $\Delta = 0$ the angular distribution between the nearest points of crossing makes 7.5°, but if it is odd, this difference is only half so large, that is 3°45′. Thus, this net proves to be very dense.

4. Determining the Orientation of the Plane of Polarization by Using the Phase Shift

Determinations of the position of the polarization plane in some structure details of the corona were made by means of photometric measurements of 66 frames defined

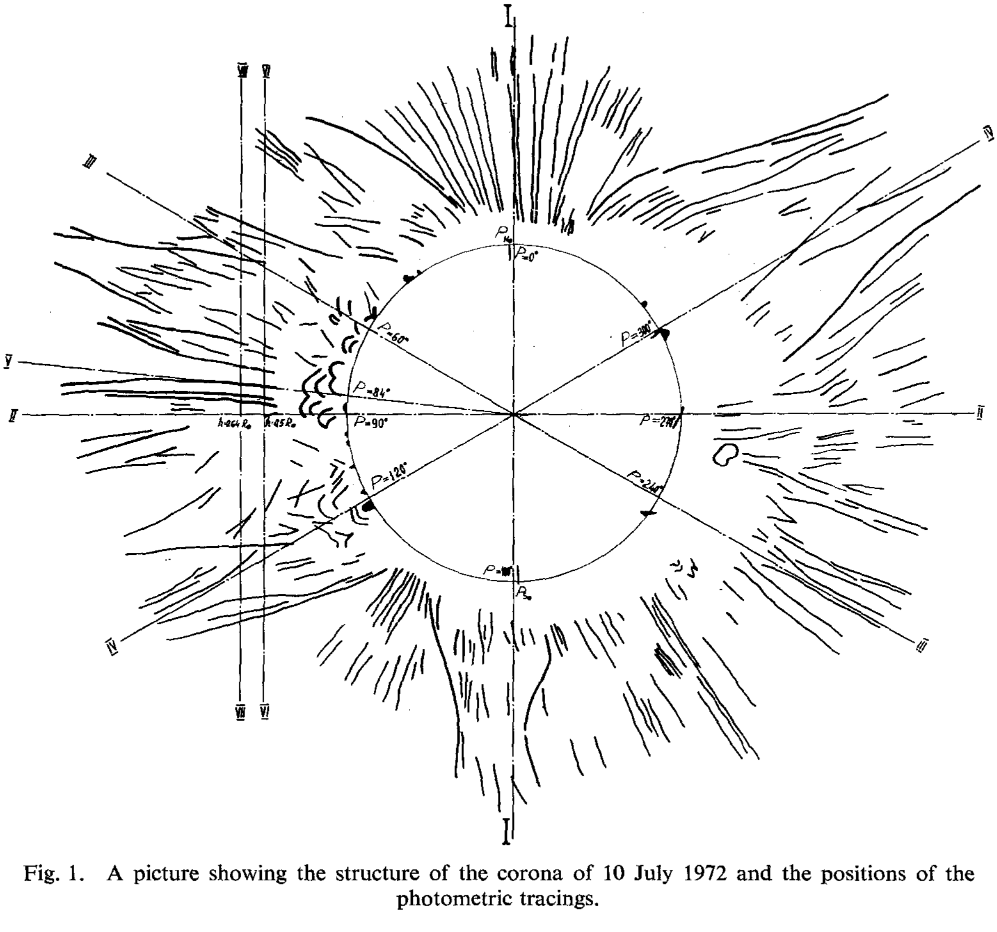

Fig. 1. A picture showing the structure of the corona of 10 July 1972 and the positions of the photometric tracings.

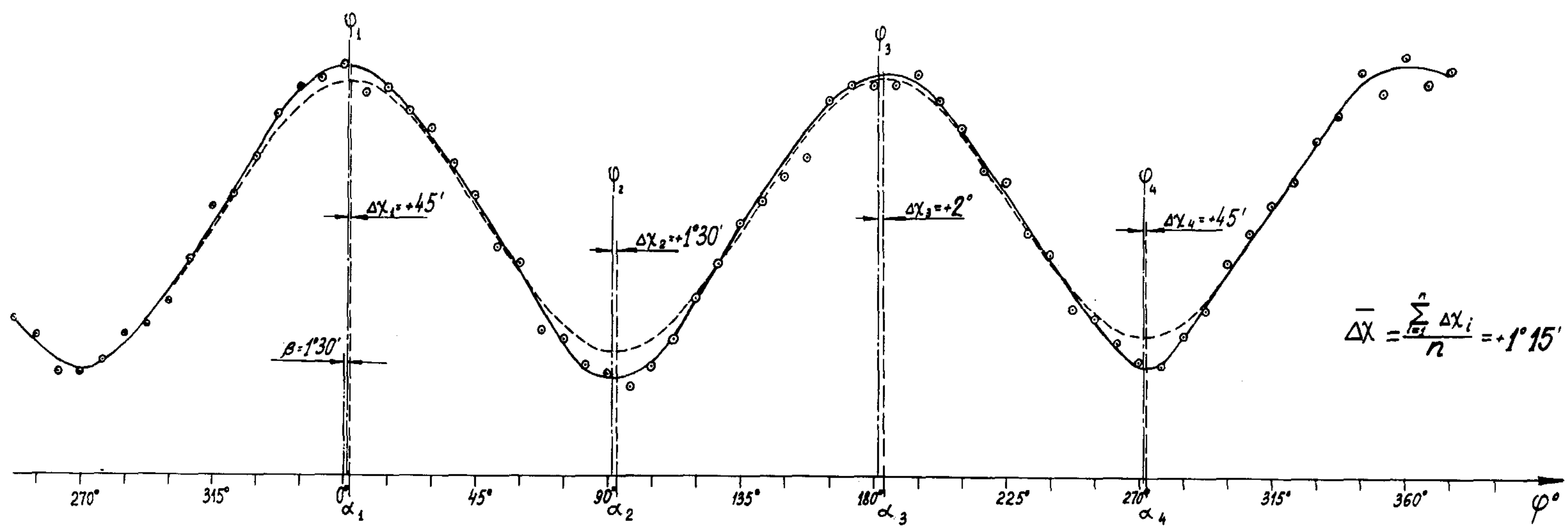

Fig. 2. Curves illustrating the determination of the phase shift, the mean phase shift and the mean-square measurement errors in the point with coordinates $P=270°$ and $h=0.97\ R_{\odot}$.

by the central phase of the eclipse. The structure picture of the corona and the positions of the photometric tracings are shown in Figure 1.

The method of determining the position of the plane of polarization consists in determining the phase of the intensity variation curve in the chosen point compared with the phase of a curve describing the polaroid rotation.

The intensity values in a given point were plotted for every frame on a scaled paper. In every point of measuring (92 in number) the curves with 4–5 maxima and minima were obtained. The positions of the maxima and minima so obtained were determined from a comparison with the curves showing the polaroid rotation. The highest significance was given to those parts of the curves which corresponded to relative angular positions of the transmission axis of the polaroid and the plane of polarization of about $\pm 45°$. After measuring the phase shift on all the parts of the curve, the values so obtained were averaged. The example in Figure 2 shows the curve representing a point which is situated on the equator (positional angle $P = 270°$) at the height $h/R_{\odot} = 0.97$ over limb (solid line). Along the abscissa the polaroid turning angles φ corresponding to the different frames are plotted and along the ordinate the intensity in relative units is plotted. The positions of maxima and minima on the empirical curve (marked $\alpha_1 \ldots \alpha_n$) were found from the dotted curve. The angles $\varphi_i \ldots \varphi_n$ correspond to the positions of the maximum and minimum transmission of the polaroid for the given photometric setting. The phase shift for this point turned out to be equal to $\Delta\bar{\chi} = +\frac{1}{4}(45' + 1° 30' + 2° + 45') = +1°15'$. By this method 92 points in the corona were analyzed.

For the estimation of the precision of the measurement the same method has been applied by measuring photographs of the solar disk itself taken with polaroid combined with strongly absorbing neutral filters in front of the camera objective. By this method the position of the transmission plane of this polaroid was determined with an error of 0° 30′.

In the case of corona photometry, the errors are accumulated from the inexact combination of photometric settings. The radial settings are made across the solar centre to reduce those mistakes to a minimum. This error was equal to about 0.03 mm on the negative which corresponds to the precision of the measurements of a phase shift of about 30′. The dimensions of the microphotometer slit was 0.07 mm × 0.07 mm. As a result of the determination of the phase shift when using all measured points (~380 half-periods of the sine-curves) a mean-square error of 0° 56′ was obtained.

5. The Results of the Measurements

Figure 3 represents two families of isophotes obtained for a half-period corresponding to the central phase of eclipse (51–56 sec since beginning of full phase). Crossings marked by points correspond to even values i–k; those marked by circles correspond to odd ones.

As is seen, the net has a regular structure, especially for the beam at N-W limb. In this region the maximum deviations do not exceed 1°, and mean-square ones are about 0.3°. Thus, in this region there are no deviations of the plane of polarization from the tangential direction.

No deviations larger than 3° were revealed in the corona. This refers to the equatorial as well as to the polar regions where the intensity gradient is essentially greater, meaning also greater measuring errors.

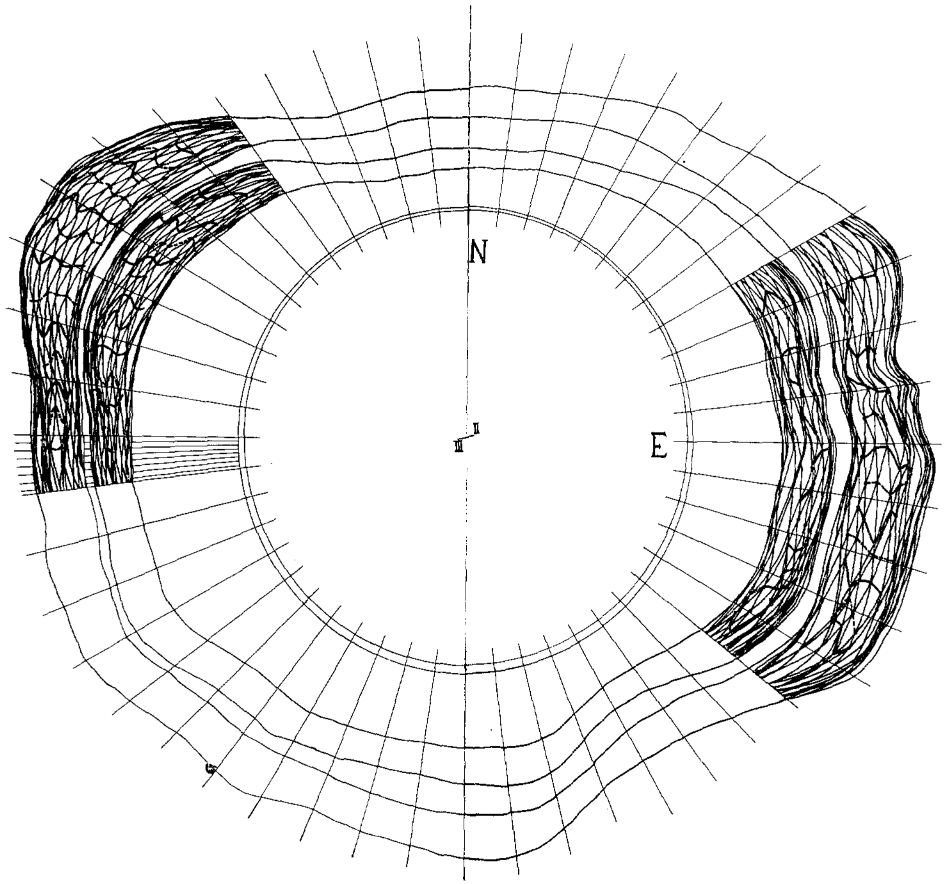

Fig. 3. Isophotes of the corona obtained through polarization filters. The radius-vector drawn from the solar center to the points of crossings of isophotes gives the direction to the polarization (H-vector) in this point.

Figure 3 shows that the regular deviations exist at the E-limb. Figure 4 gives the deviations $\Delta\chi$ for this region. Curves 1 and 2 have been obtained as a result when averaging 4–5 points for φ_i-$\varphi_k \approx \pi/2$. In fact both curves display a common tendency: the polarization plane near the equator does not deviate from the normal position, and with the motion in latitudinal direction the turn of the polarization plane is slower than would be expected according to the classical theory. Such a phenomenon could

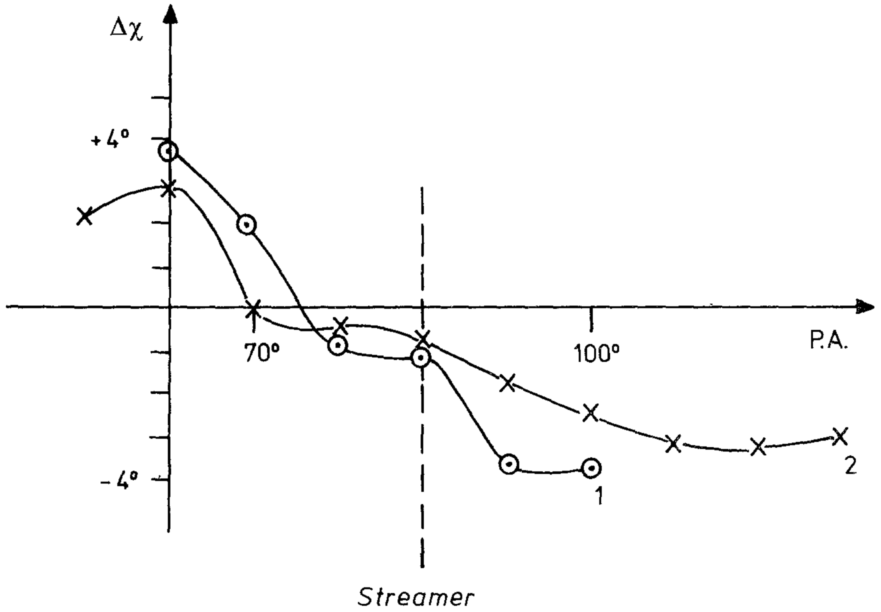

Fig. 4. Deviations in the position of the plane of polarization for the inner (1) and outer (2) families of isophotes on the E-limb.

be observed if the poles were brighter than the equator* or if an intensity decrease takes place near the equator (for example, in a large spot).

Values of the deviations of the polarization plane in the structure details for all measured photometric 92 points are represented on the graphs of Figure 5.

In Figure 5(b) for every photometric section the deviations $\Delta\chi$ are given for different heights $h/R_\odot$ over the solar limb (point 'O'). The zero line coincides with the direction of the section. Positive deviations correspond to the clockwise direction. The scale of deviations is indicated. The dotted line means that the values of the deviations obtained are less reliable because they are obtained by 2–3 half-period.

From the analysis of the curves of Figure 5 it can be concluded that the values of the deviations of the plane of polarization from the tangential direction are trustworthy because the dispersion is small. Two tangential photometric sections at different distances 0.5 $R_\odot$ and 0.64 $R_\odot$ from the solar limb are made in addition. The values of the deviations of the plane of polarization determined at intervals of 5° in position angle for these sections are shown in Figure 5(a). In both pictures of Figure 5 the symbol ⊗ (a cross in a circle) means the values obtained in the same points but from the other photometrical sections. These values coincide sufficiently well within the limits of the measuring errors. The maximum difference does not exceed 30′. From

* According to Kuiper (1957) a comparison of brightness distribution along the solar disk in equatorial and polar directions has been performed twice, but in one case it gave an opposite effect (~1 %), and in another case no difference was revealed.

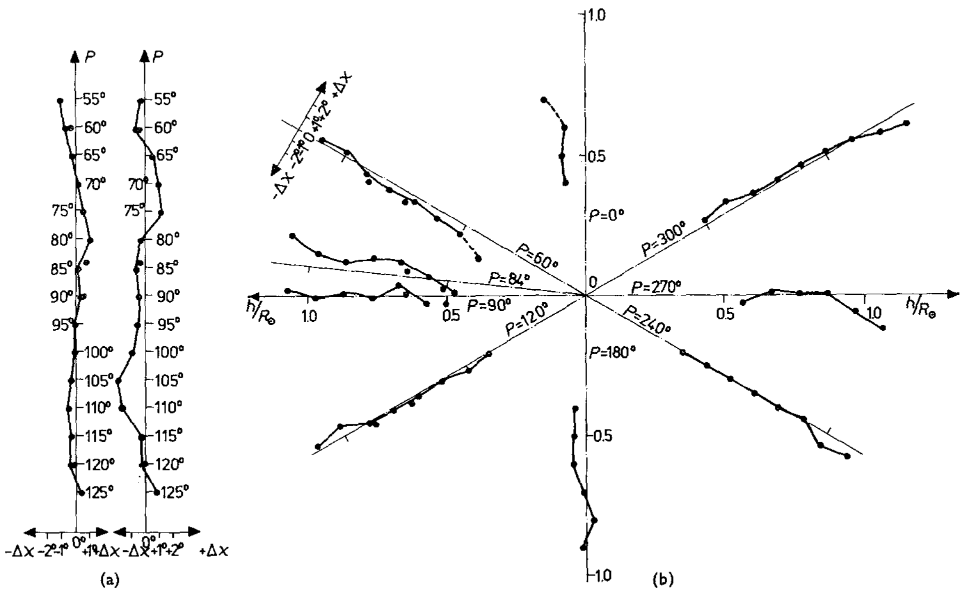

Fig. 5. The deviations in the orientation of the plane of polarization obtained photometrically along the directions indicated on the structure picture (Figure 1).

a comparison of both curves of Figure 5(a) one can see that with increasing distance from the solar limb the deviations are diminished but the shape of the curves will remain the same.

The change in the deviations with latitude, that is the curves in Figure 5(a) in the zone approximately $\pm$ 25° from the equator to the north, is positive while from the equator to the south it has negative values (i.e. the plane of polarization is deviated in different directions from the equator). This is in complete agreement with the results of the treatment by means of polarizational isophotes. The peculiar shape of the deviation curves at distances $h/R_\odot \geqslant 1$ should be also noted.

6. The Possible Origin of the Turn of the Plane of Polarization in the Corona

1. F-component

As the F-component of the corona has its own polarization (Öhman, 1947) the possibility of the turn of the plane of polarization as a combined effect of the F- and K-components should be examined. In principle, the turn may appear if the preferential vibrational directions of the two constituents are oriented arbitrary. But in the given case (according to Öhman, 1947) the planes of polarization are perpendicular to each other and one can easily see that the turn can not be obtained by superposition.

2. The influence of the electron velocity

The deviation of the plane of polarization (according to the paper by Molodensky,

1973) by $\sim 2°$ corresponds to the motion of the electron streams with the velocity V_T (the thermal one at the temperature $T = 2 \times 10^6$K). From the obtained data one can see that in the outer corona ($h/R_{\odot} \geqslant 0.5$) there are no signs of the existence of electron streams with the velocity of about V_T in points in which the measurements had been made.

3. The effect of inhomogeneity of the photosphere radiation field

While the Sun is considered as an ideally homogeneous luminous ball, the vibrational direction in the corona must be associated with the tangential direction of the limb. With a high degree of accuracy this conception corresponds to what is observed. But if we consider deviations of some angular degrees, and only in selected regions of the corona, then it would make sense to calculate corrections to the classical theory developed by Baumbach (1938) by taking into consideration the effect of facular fields and spots.

Our calculation will refer to the turn of the plane of polarization in the case when an inhomogeneity exists at the limb (see Figure 6) and with an area S and a contrast $1+K$ (where $K>0$ for the facula, and $K<0$ for the spot). We simplify our calculation by considering only the regions of corona lying in the plane perpendicular to the line of sight and crossing the solar centre. Let θ be the heliocentric latitude of the spot centre, and θ_1 the angle between the direction towards the Sun and the direction towards the spot in the considered point of corona 'A'. This point is located at the

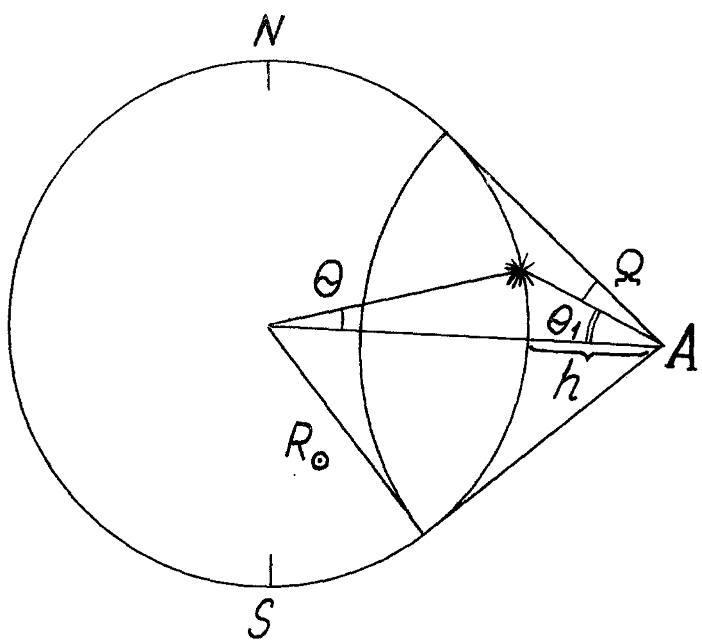

Fig. 6. A graphical presentation of quantities used for the calculation of the turn of the plane of polarization caused by an inhomogeneity in the radiation field of the photosphere.

height h over the solar surface (Figure 6). Between the introduced values we have a relation:

$$h \tan\theta_1 = R_\odot \sin\theta . \tag{9}$$

The solid angle formed by the area of a spot when observed from A is equal to

$$\omega = \frac{S \cos(\theta + \theta_1) \sin^2\theta_1}{R_\odot^2 \sin^2\theta} . \tag{10}$$

The solid angle occupied by the solar disk when obsserved from A is equal to

$$\Omega = 2\pi(1 - \sqrt{1 - r^{-2}}), \tag{11}$$

where $r = 1 + h/R_\odot$.

These angles apparently define the relative weights with which the whole disk radiation and inhomogeneity are represented in the radiation in point A.

$$\frac{I_{(\text{inhom.})}}{I_r + I_t} = K \frac{\omega}{\Omega} . \tag{12}$$

As far as the radiation of the inhomogeneity is concerned producing polarization with the plane turned by an angle θ_1, then the relation (see Figure 6) may be written:

$$I_{(\varphi)} = I_t \cos^2\varphi + I_r \sin^2\varphi + I_{(\text{inhom.})} \cos^2(\varphi - \theta_1), \tag{13}$$

where $I_{(\varphi)}$ is proportional to polaroid transmission oriented under angle φ to the tangential direction. The components I_r and I_t are connected as

$$I_r = I_t \frac{1 - p}{1 + p}, \tag{14}$$

where p is the polarization degree. From expression (13) it is not difficult to find the direction of preferential oscillations of the electric vector. If we differentiate $I_{(\varphi)}$ by φ and put the result equal to zero, we get the maximum of expression (13).

Designating the turn of the plane of polarization by δ and taking into account that it is small we get

$$\delta = - \frac{\sin 2\theta_1 \, \omega K}{2p\Omega} . \tag{15}$$

This expression may include also the effect of disk darkening towards the limb (Baumbach's classical calculation included this effect) if with Ω we understand not only the solid angle but also the dilution coefficient calculated with regard to this effect. In this case Ω proves to be somewhat less than the solid angle (for $\lambda > 5000$ Å to the coefficient 0.8).

As an example of possible values, let us substitute some average data in these formulae. Let $h = 0.3\ R_\odot$, then the polarization $P = 0.2$; Ω by formula (11) will be 2.23. Let the spot have the contrast $K = -1$ and the area 10^{-3} from the area of the hemisphere 2π; then $\omega = 4 \times 10^{-2}$, and

$$\delta = 4.3 \times 10^{-2} \sin 2\theta_1 . \tag{16}$$

Thus, with $\theta_1 = 45°$ and neglecting the disk darkening towards the limb the angle $\delta = 2.5°$. Taking the darkening into account one gets $\delta = 3.1°$. Therefore the presence of large spots may explain large-scale anomalies in the polarization plane position.

As one can see from the synoptical map of the Sun of 10 July 1972, near the E-limb (but behind it) at the distance of 10°–20° there were three groups of spots with the total area 800×10^{-6} in units of the disk area. A thin coronal beam was projected to the line connecting two groups, and so it is close to the axis of symmetry of inhomogeneity of the field of photospheric radiation. In Figure 4 this beam is marked. There is a qualitative agreement between the observed deviations and the calculated effect. Indeed: (1) the signs of deviation correspond to the decrease in brightness, (2) above the spot there are no deviations, (3) the deviations decrease with height. As for the quantitative comparison, it is rather difficult because of low precision of the extrapolation of the spot areas behind the limb. Finally, the region of the NW-beam in which no deviations are obtained is situated above a large calm area of the photosphere.

7. Conclusion

In the authors' opinion the above determinations of the orientation of the plane of polarization in the corona are the most exact ever obtained. This includes not only photographic measurements but also the photoelectrical ones (Ney *et al.*, 1960; Ney *et al.*, 1961). The errors in these works were 1.2°–2.4°.

The obtained deviations in the position of the polarization plane which have been obtained from photographical measurements (10°–20° and above) by some authors can be explained as accidental errors. The deviations of the order 1°–3° may be considered as real.

The observed deviations in this paper at the E-limb can be attributed to the influence of the group of spots causing the inhomogeneity of the field of the photospherical radiation. The authors have not been able to find possible sources of the polarization plane deviation in the outer corona.

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