Measuring the polarization of the solar corona

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We have measured the position of the plane of polarization in the star corona during the total solar eclipse of 11 July 1991. We used a rotating polaroid whose transmission axis was aligned at an angle of 45° to the radius. The plane of polarization is everywhere tangential to the solar surface to within 1°.

1. INTRODUCTION

Investigating the polarization of continuum emission from the corona during observations of solar eclipses enables one to form an idea of the topology of the corona1-5 and the physical features of its electron component.6,7 Ordinary polarization observations are based on acquiring three photographs with different analyzer (polaroid) positions. The errors in determining the degree of polarization in this case are usually ΔP ≈ 10% and the errors in determining the direction of polarization are Δα ≈ 10°.

The results of such research have shown that the polarization of the K corona as a whole corresponds to Thomson scattering of photospheric photons from free electrons in the corona, as represented by van de Hulst’s model,6 for example. The degree of polarization first increases with distance from the limb, reaching a maximum P ≈ 50% at ρ ≈ 1.5 R☉, and then decreases slowly;7 the direction of polarization coincides with the tangent to the limb. More detailed observations, however, led to the discovery of regions in the inner corona in which the degree of polarization is P > 80%, which exceeds the maximum theoretically possible value,9-11 as well as regions in which the departure of the plane of polarization from the tangential direction exceeds 10° (Refs. 11 and 12).

Interpreting such deviations forces one to assume that streams of fast electrons exist in the corona,12 and polarization observations could thus become a good instrument for detecting such streams. The question of the reliability of measurements and a significant increase in their accuracy becomes pointed in this connection.

To increase the accuracy in determining the degree of polarization P, a new measurement method was first carried out in Ref. 13 using two circular sectoral analyzers, which consists in the following. A disk, consisting of sectors that are polaroids oriented so that the transmission axis of a polaroid coincides with the central radius of each sector, is placed in front of the image of the corona. The center of the analyzer disk is matched with the center of the solar disk, and the analyzer is rotated to eliminate the influence of irregularities of the individual sectors. A second photograph is made with an analyzer in which the polaroid axes are perpendicular to the central radius in each sector. Measuring the intensities of transmitted light at a given point of the corona in the two photographs enables one to determine the degree of polarization

\[ P = \frac{K(I_e - I_f)}{I_e + I_f}, \]

where \( I_e \) and \( I_f \) are the intensities of light passed through the analyzers with radial and tangential polaroid axes and \( K = \beta \sin \beta, \) \( \beta \) being the angle of a sector. For a sufficiently large number of sectors, \( K \) is close to unity. In Ref. 13 it was shown that the reduction in polarization due to the coefficient \( K \) [taken into account by Eq. (1)] for \( n = 6 \) and \( n = 12 \) is

\[ n_6 = \frac{6}{\pi} \int_0^\pi \cos^2 \theta d\theta = 0.885, \]

\[ n_{12} = \frac{12}{\pi} \int_0^\pi \cos^2 \theta d\theta = 0.978. \]

Thus, \( n = 12 \) sectors yields virtually a radial polarization filter [with a 2.2% error, which is taken into account by Eq. (1)]. Following Ref. 13, this method gained wide popularity, and in the present work we have used a modification of it that enables us to measure the orientation of the plane of polarization (the departure from the tangential direction) by subtracting two images.

During an eclipse, one usually makes several pairs of photographs with different exposures, so that the required range of distances in the corona is covered by linear segments of the characteristic curve of the negatives, or one uses a filter with a transmission coefficient that varies radially, compensating for the considerable brightness gradient of the corona.

Movie photography of the corona through a rotating polaroid, suggested in Ref. 14, is a method that considerably increases the accuracy in determining the position of the plane of polarization. The error in measuring the direction of the plane of polarization is ~ 1°. The method requires considerably more photographic data than usual, however, which greatly complicates the analysis. Moreover, the measurements are carried out at individual points, whereas the regions in which the plane of polarization departs from the tangential direction apparently have small angular sizes, which makes this method ineffective for detecting them.

2. PHOTOGRAPHIC METHOD FOR ACCURATE DETERMINATION OF THE POSITION OF THE PLANE OF POLARIZATION

If we modify the method of Ref. 13 by arranging the transmission axes of the polaroids symmetrically at an angle \( \varphi \) to the central radius of the sectors, then the difference between the intensities at each point of two images of the corona will equal zero in the absence of deviations (\( \alpha = 0 \)), and for \( \alpha \neq 0 \) we will have

\[ \delta I = I_e - I_f = 2I_e \alpha \sin 2\varphi, \]

where \( I_e, I_f, \alpha \), and \( \varphi \) are the intensities of light passed through the analyzers with radial and tangential polaroid axes and \( \alpha \) being the angle of a sector. For a sufficiently large number of sectors, \( \alpha \) is close to unity. In Ref. 13 it was shown that the reduction in polarization due to the coefficient \( \alpha \) [taken into account by Eq. (1)] for \( n = 6 \) and \( n = 12 \) is
where $I_p$ is the intensity of polarized light. This difference is largest for $\varphi = 45^\circ$, which corresponds to the best arrangement of the polaroids. With allowance for the finiteness of the angle $\beta$ of the analyzer sectors, for $\varphi = 45^\circ$ we should replace Eq. (2) by

$$\delta I = 2I_p \sin \frac{\beta}{2} \cdot \frac{\sin \beta}{\beta}.$$  

(4)

Since $\delta I$ is proportional to the angle of deviation $\alpha$, we can use photographic subtraction of the two images. Inequality of intensities immediately indicates a departure from tangential polarization. Assuming that regions with a $\sim 1-2\%$ relative change in intensity can be revealed, and taking a degree of polarization $P = 50\%$, from (4) we obtain $\alpha \approx 0.25\% - 0.5\%$, which is the sensitivity of the given method.

3. DETERMINATION OF THE DEGREE OF POLARIZATION

It turned out that the degree of polarization of the corona reaches 50% in some regions. This means that the intensities of coronal radiation will differ threefold after passage through the tangential ($T$) and radial ($R$) analyzers, since

$$\frac{i_T}{i_R} = \frac{1 + P}{1 - P}.$$  

(5)

(we set $K = 1$ for simplicity).

Such a large difference between the densities of the negatives can make it necessary to use $R$ and $T$ photographs made with different exposures, which increases the errors in determining $P$. To achieve greater accuracy in photographic comparison, the densities of the negatives should be similar. For this purpose, the tangential analyzer must be stopped down in accordance with Eq. (5), taking for $P$ the distribution of the degree of polarization in the corona based, for example, on van de Hulst's $P = P_H$ model. The stop factor $S(\rho)$ is then determined as follows:

$$p = \frac{S(\rho)}{S(\rho) + 1},$$  

(6)

If the polarization distribution in the actual corona corresponded exactly to the model, two identical photographs would be obtained. In reality, the degree of polarization at each point will be determined by the ratio of intensities after the radiation passes through the $R$ and $T$ analyzers,

$$p = \frac{S(\rho)/i_R - 1}{S(\rho)/i_R + 1},$$

where $S = (1 + P_H)/(1 - P_H)$. The measured intensities $i_T$ and $i_R$ appearing in Eq. (6) do not differ greatly, and the main "load" falls to $S$; but this is an instrumental function, which is known with any required accuracy, in principle.

4. OBSERVATIONS OF POLARIZATION OF THE CORONA ON 11 JULY 1991

An instrument implementing the method suggested in Ref. 14 was built to observe the eclipse of 11 July 1991. The telescope, on an equatorial mount, had a doublet objective 15 cm
in diameter with a focal length 225 cm. At the prime focus we placed a cassette containing a 13×18 cm ORWO WP1 photographic plate, on which we made two successive photographs at two orientations of the polaroid (±45°), which was placed in front of the focal plane. A rotating opaque disk contained two windows shaped so as to increase the polaroid's transmission coefficient with distance from the center (rather than being straight sectors) in accordance with the decreasing brightness of the corona, thus acting as a radial-density filter.

The observations were carried out in the southern part of Baja California in Mexico, near the town of La Paz. During totality, we obtained three pairs of photographs with exposures of from 5 to 45 sec. In Fig. 1 we give one of two photographs of the corona that were obtained with the maximum exposure. Long coronal rays are distinctly visible over the camera's entire field of view (5 R⊙). The spatial resolution on the negative is ~10°.

The difference between the Φ = +45° and −45° photographs, obtained by photographic subtraction, is given in Fig. 2a. In Fig. 2b we give the difference, obtained by the same means, for two identical Φ = +45° copies. Traces of the corona can be distinguished in both figures. It is obvious that a zero difference in subtraction is achieved with a certain error, and we must estimate what departures of the plane of polarization from the tangential direction correspond to changes in optical density in Fig. 2. The factors that degrade the subtraction result include the following: 1) inaccuracy in satisfying the condition γ = 1 on the duplicate negative; b) the use of non-linear segments of the characteristic curve of the emulsion (unavoidable, despite the use of a radial-density filter); c) the complexity of exact matching of the duplicate negatives — an operation with three degrees of freedom; d) a small difference between the positions of the polaroid rotation axis relative to the center of the solar disk in the Φ = +45° and −45° photographs.

To calibrate the instrument, we made photographs of a source with a given polarization. In front of a frosted glass, which scatters the light from a point source, we placed a fan of strips of polaroid film, cut along the transmission axis and at 2°, 4°, and 10° angles to it. An image of the source was constructed in the focal plane of the instrument using alignment optics. We then carried out the same procedure of photographic subtraction as for photographs of the corona.

In Fig. 3 we give the results of photometry of the photographic differences. Curve 1 corresponds to subtraction of identical photographs of the film and determines the "noise
level." Curve 2 demonstrates the variation of optical density for a $\pm 2^\circ$ change in the direction of polarization. Curves 3 and 4 are photometric profiles of the differences shown in Fig. 2a and b, respectively. A comparison of these curves shows that there are no deviations of the direction of polarization from tangential greater than $1^\circ$ in the corona.

5. STRUCTURE OF THE CORONA

The good quality of the photographs of the corona obtained in the polarization experiment enables us to use them, together with observations obtained at Mauna Kea in the Hawaiian Islands and at Tefé in Brazil, to analyze the fine structure of the corona. These three sites are spaced out along the eclipse path so that, owing to the time difference in the onset of the total phase, we can trace changes in the structure over 3 h.

A structural drawing of the corona by S. Koutchmy is given in Fig. 4. The overall shape of the corona on 11 July 1991 is completely unlike that expected for the corona at an epoch of a maximum of the solar activity cycle. Instead of an almost symmetric shape, on 11 July the corona had an elongated appearance, more typical of an epoch of a minimum, with the only difference that the long rays or streamers extend not only in the equatorial plane but almost perpendicular to it. This corresponds to the heliospheric layer being "disturbed" or almost orthogonal to the equatorial plane.

The twisting of two coronal rays above the western limb is also unusual. In the materials obtained at La Paz and Mauna Kea, the rays are twisted, as seen in Fig. 4, whereas according to the Tefé data, they are evened out. This change occurred in no more than 135°54. This area was located above an active region that was characterized by strong flares; intense emission in the yellow Ca XV line was detected with the NSO/SP photometer 0.5 and 1 rotations before the eclipse.

One of the streamers has a sharp eastern edge, in contrast to the diffuse edges of the other streamers. This sharp edge, seen in films from the three stations, existed for at least 3 h. It is probably a tangential discontinuity of the magnetic field, making it possible to see the streamer "end on."

A multitude of dark holes are seen in the corona. A large cavity is seen around the faint prominences above the eastern limb.

6. CONCLUSION

We have presented the main results and methods of measuring the polarization of the corona. Our interest was concentrated on determining the orientation of the plane of polarization. The measurements, based on a procedure not used by anyone before, showed that the direction of polarization was tangential to the solar limb to within $1^\circ$ everywhere in the corona on 11 July 1991. At the same time, the problem of determining the degree of polarization is also of great interest in at least two respects.

1. It has not yet been established whether regions exist in which the polarization exceeds the maximum possible value (in Thomson scattering).

2. No satisfactory procedure for reconstructing the three-dimensional structure of the corona has yet been developed.

The first problem is of fundamental interest: in fact, any indication that the degree of polarization exceeds the maximum possible value means that the nature of coronal emission may be different from what is generally accepted.

The second problem is of a more practical nature. Obtaining a three-dimensional picture of the electron distribution in the corona — a still unsolved problem — has great prospects, however. A continuous transition from the outer regions of the corona to the heliospheric current sheet presents one of the most important modern problems of solar physics. It is of fundamental importance to establish the fact that the porosity of the emission is high, so that the concept that coronal emission comes from some surface, perhaps fairly complicated, can be considered a good first approximation. This creates