Direction of the coronal green line polarization as derived from the eclipse measurements

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Abstract. Investigation of the polarization in the coronal FeXIV λ 530.3 nm line is continued by exploiting the 11 July 1991 eclipse observation. In this paper, we analyze the direction of the plane of polarization represented by deviations of the magnetic vector from the radial directions – angle β. The relation of this angle to the other polarization charcteristics is discussed. It has been found that β is small in the coronal features characterized by a high degree of polarization (streamers and coronal holes). With the decreasing polarization (e.g., when the equatorial objects of enhanced activity are considered) the magnitude of β increases significantly. The extreme values of β are observed within the coronal features related to the active regions in the photosphere. The distribution of β in magnitude is distinctly shifted from zero to positive values. This means that, in the most part of the corona on July 11, 1991, the magnetic vector deviates from radiality clockwise. In connection with the revealed drastic discrepancy between the observed direction of the plane of polarization and the generally accepted theoretical conceptions (Badalyan et al., 2001; Badalyan, 2002), the obtained result may be worth considering when developing a new theory of the origin of polarized radiation in the coronal green line.

Key words: coronal green line – polarization charcteristics – direction of polarization

1. Introduction

This paper makes progress in our attempts to describe the characteristics of polarization in the coronal green line by using high-quality data obtained during the total solar eclipse of July 11, 1991. The measurements of coronal polarization performed both in the continuum and in the emission lines contain valuable information on the physical conditions in the coronal plasma. Any observation of the coronal green line FeXIV λ 530.3 nm is related to the component of the corona with the temperature $\sim$ 2 MK, which is the most usual value in the loops of the inner corona. The chance to study the intensity and structure of the coronal magnetic fields by measuring the green line polarization is of great importance, as well. At present, there are no direct methods of measuring the magnetic field in the corona. The coronal magnetic field may be deduced from theoretical calculations performed under some simplifying assumptions (e.g., a force-free or potential field) and using the observed field distribution at the photospheric level. The estimates of the coronal magnetic field can be obtained from radio data (see, for example, Gelfreikh et al., 1997). However, it is also possible after a certain simplification of the radiation mechanism, and this procedure is mainly applicable to rather strong fields.

During the eclipse on 11 July 1991, polarized filtergrams detecting the λ 530.3 nm emission line radiation and the polarized white-light images were obtained (Sýkora and Badalyan 1992; Sýkora et al., 1994). At the day of the eclipse, the corona was in the close-to-maximum phase of solar activity. In spite of this, an unusually flattened form of this corona, connected with a strongly inclined global magnetic dipole, was detected. As a result, huge streamers were observed at high solar latitudes in the plane of the sky (see the upper part of Fig. 1). They were spatially separated from the not very bright coronal condensations recorded in the equatorial region. Such favourable conditions offered an opportunity of investigating these large-scale coronal features separately from each other. A medium-size coronal hole was situated west of the north pole. At the east limb (position angle $P \sim 150°$), a region of reduced brightness similar to coronal holes was present. At the same limb ($P \sim 75°$) to the north, a short bright streamer was observed with a bright condensation at its base.

After processing the filtergrams, Badalyan and Sýkora (1997a) and Badalyan et al. (1997) constructed the distribution maps of polarization for the entire inner corona. A detailed analysis of this map revealed a number of new interesting peculiarities in the distribution of the polarization and intensity of the green line. The principal results of this analysis are described in our earlier papers (Badalyan and Sýkora, 1997a, 2001; Badalyan et al., 1997; Badalyan et al., 1999a, 1999b, 1999c). Comparison of our results with those reported by other authors made in Badalyan and Sýkora (1997b) and Badalyan et al. (1997) has shown that some regularities in the behaviour of the green-line polarization agree well with the results obtained earlier (Hyder et al., 1968; Arnaud, 1977, 1982; Picat et al., 1979).

One of the most valuable findings was the anticorrelation between the degree of polarization and the green line intensity (Badalyan and Sýkora, 1997a). This dependence was then studied in more detail by Badalyan et al., (1999a) and Badalyan and Sýkora (2001). It was shown that, if we consider the points within a narrow ring at a fixed distance from the disk centre, the anticorrelation dependence in the p–$\log I_\lambda$ diagram splits into two branches with an empty zone ("a zone of avoidance") between them. The points pertaining to the large-scale coronal structures of different morphological (i.e. physical) types form the separated "clouds" (clusters) of points on that diagram. This means that the

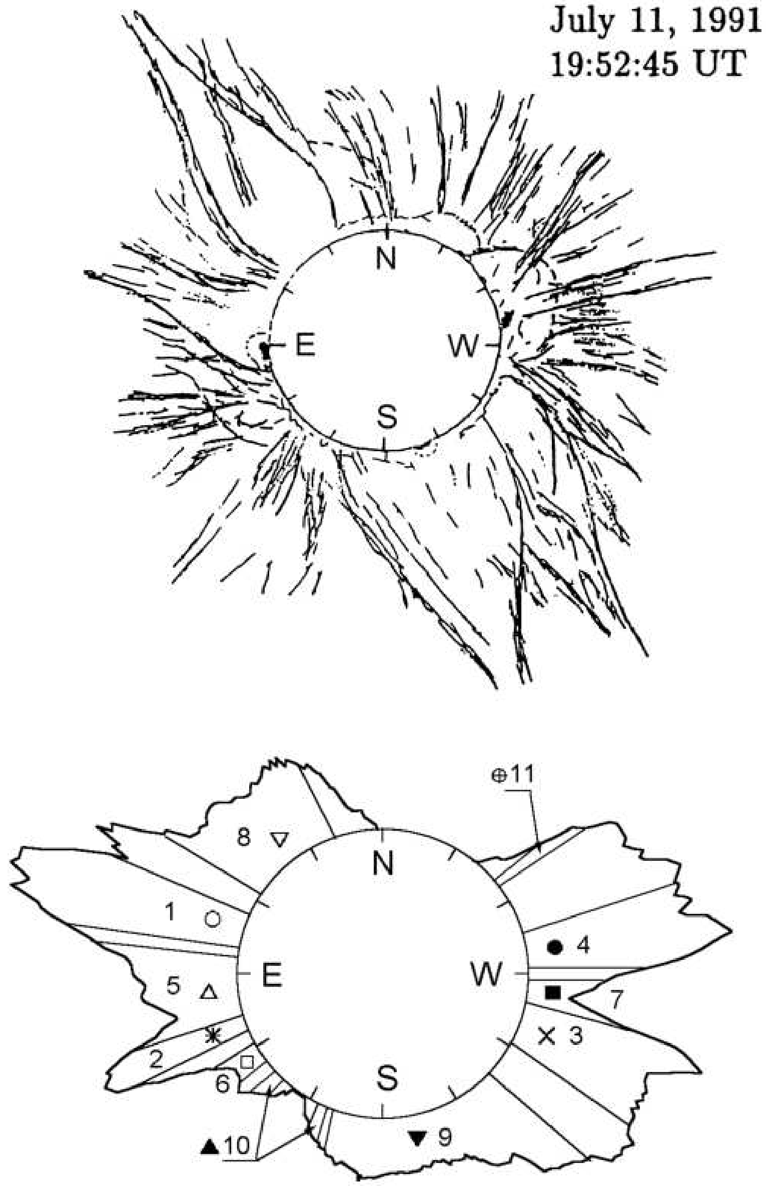

Figure 1. The structure of the white-light corona as observed during the 11 July 1991 solar eclipse (upper panel) and the intensity contour of the green line corona as measured around the limb at a distance of 1.2 $R_{\odot}$ (lower panel). The distance of the contour from the limb represents the line intensity, the radius of the sun being 25 absolute coronal units of the intensity. Intervals of the position angles of the large-scale coronal structures under consideration are shown, as well as the corresponding signs used in Fig. 5 to identify the points related to these structures (see also Table 1).

behaviour of the polarization of the green line is substantially different in the individual structural features in the lower corona. It may be due to the fact that the degree of the line polarization decreases as the role of electron collisions in the line excitation grows; i.e., the contribution of the unpolarized component to the line intensity becomes greater. At the same time, the growth of this component results in the increasing line intensity I_λ.

The found peculiarities in the distribution of the degree of polarization p and the green line intensity I_λ in different large-scale structures in the corona indicate that we are probably dealing with the direct influence of the magnetic field on the polarization characteristics of the coronal green line here.

A further study (Badalyan et al., 1999a; Badalyan and Sýkora, 2001) indicated that this effect was different in the equatorial regions and in the high-latitude streamers. We have found that the anticorrelation dependence splits into two branches when the diagrams $p - \log I_\lambda$ are drawn only for the points within a narrow ring limited to a certain fixed distance from the solar disk centre (to exclude the well-known dependence of polarization on the distance from the solar disk). The upper branch is basically related to the huge high-latitude streamers, while the lower one contains the equatorial regions. Each of the branches may be considered as a complex of the clouds of points, related to the individual large-scale coronal features. The points characterized by small intensities and large polarizations on the diagram correspond to the regions in the vicinity of coronal holes. The two branches related to different types of the coronal structures are evidently present throughout the height interval under consideration, though the relative position of the branches varies rather significantly for narrow rings at different heights (for more details see Badalyan et al., 1999a and Badalyan and Sýkora, 2001).

In the present paper, the third characteristic, namely, the direction of the green line polarization is investigated in more detail. The direction of the plane of polarization as derived from our measurements (i.e., the direction of predominant oscillations of the magnetic vector in a wave) proves to differ crucially from the generally accepted theories (see, e.g., House, 1974; House et al., 1982; Lin and Casini, 2000). We have found that, in the high-latitude streamers characterized by a large degree of polarization, the direction of the magnetic vector practically does not deviate from the radiality; i.e., it is the same as in the case of polarization measured in the white light radiation. The measured values of β are rather large only in the bright coronal condensations, where the degrees of polarization were found to be small.

The problem was discussed in detail in Badalyan et al. (2001) and Badalyan (2002). It was shown that, in fact, no reliable observational evidence was available to corroborate the existing theoretical speculations concerning polarization in the coronal emission lines. We also arrived at the conclusion that the well-known results of Picat et al. (1979), who studied the direction of polarization using the green line eclipse observation of 30 June 1973, did not actually differ from our findings, in spite of the opposite statement of the authors. It is to be noted that the methods of acquiring data and eliminating the white-light contribution in (Picat et al., 1979) are similar to ours.

In the context of a serious physical problem thus arising, the results obtained in the present work may be useful in developing a modified theory of the origin of polarized radiation in the coronal green line. This is particularly important because, as follows from Badalyan et al. (2002), the magnetic field significantly affects all characteristics of polarization in the green line. Consequently, the polarization observations in the coronal emission lines could become a promising tool for the investigation of the coronal magnetic field.

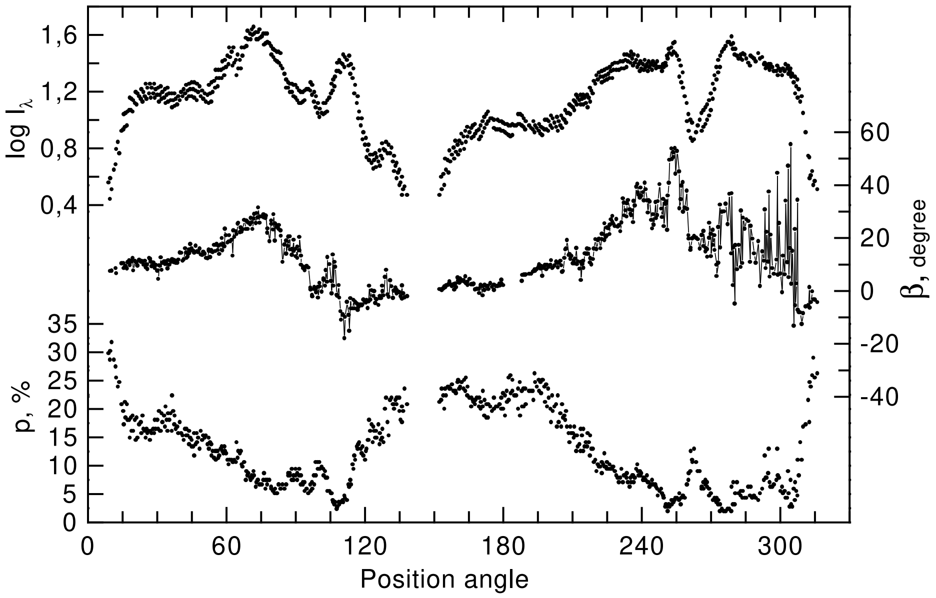

Figure 2. Variations of the degree of polarization of the green line intensity $\log I_\lambda$ (upper left scale), the deviation angle of the plane of polarization from the radial direction β (right scale), and the degree of polarization p (lower left scale) along the solar limb. As usual, the position angle is counted from the north pole of the Sun to the east, south, and west. This graph is constructed for all points inside a ring 0.03 $R_\odot$ wide at a mean distance of 1.2 $R_\odot$ from the disk centre.

2. Orientation of the plane of polarization in the 11 July 1991 corona

The angle of direction of the plane of polarization α (position angle of the magnetic field vector) was determined using four intensity matrices of the polarized radiation obtained from photometric processing of the coronal images taken in the light of the green line λ 530.3 nm (see the formula in Saito and Yamashita, 1962):

$$\tan 2\alpha = \frac{I_2 - I_4}{I_1 - I_3}. \tag{1}$$

Here, I_k is the intensity measured at physically the same point of the image taken with the polaroid in the k position. The α values are defined according to the signs of $\sin 2\alpha$ and $\cos 2\alpha$. Such a definition of α implies that the I_1 component corresponds to the orientation of the polaroid axis to the north pole. Then, at the east limb, α changes from $0°$ to $180°$ proceeding from the north to the south pole. At the west limb, the value of α derived from eq. (1) changes within the same limits, but from the south to the north pole. It means that, at the west limb, we must add $180°$ to all values of α to obtain its variation from $0°$ to $360°$.

The angle of deviation of the plane of polarization (magnetic vector in the wave) from the normal to the solar limb is $\beta = P - \alpha$, where P is the position angle of a given point from the north pole to the east, etc. The angle β defined in such a way differs from that used by Badalyan et. al (1999b, 1999c). In those papers, β was considered positive when the plane of polarization deviated towards the neighbouring pole (to the north pole in the northern hemisphere and to the south pole in the southern hemisphere); when the deviation was towards the solar equator, β was considered negative.

Fig. 2 demonstrates variation of the three polarization characteristics as a function of the position angle. The figure was obtained using all points within a ring 0.03 $R_\odot$ wide at a mean distance 1.2 $R_\odot$ from the disk centre. The total number of points was about 650. Fig. 2 allows us to trace the above-mentioned peculiarities in the distribution of p, β, and $\log I_\lambda$ along the limb. One can readily see a non-random large-scale variability of the parameters under examination depending on the position angle. The points form almost smooth curves with a very low dispersion, which is indicative of a good internal coincidence of the corresponding rows of data. The "non-zero" wideness of the band of points (particularly well pronounced on the $\log I_\lambda$ curve) is connected with the chosen width of the ring of points and reflects, in fact, a slow continuous change of the corresponding quantities with the height above the limb. Only in the SW-quadrant, a considerable dispersion of β may be noticed which, possibly, is connected with the presence of a certain number of the fine coronal rays and loop structures in this interval of the position angles. The degree of polarization is determined to an accuracy of $1.5 - 2\%$ (for more detail, see Badalyan and Sýkora, 2001). Fig. 2 shows the anticorrelation dependence between the degree of polarization p and the line intensity I_λ, as well as between p and the absolute values of β. On the contrary, a direct correlation is seen between I_λ and the absolute values of β: the higher the line intensity at a given point of the corona the larger the deviation of the plane of polarization from the radial direction.

In addition, four extremes can be identified in the I_λ curve. They are arranged in pairs at the antipodal latitudes of about $\pm 20°$ from the equator and coincide with the positions of the bright coronal condensations. The coronal condensations are related to the active features that were observed at the limb on the day of the eclipse and are also well pronounced on the Kitt Peak, Mt. Wilson, and WSO Stanford magnetograms. In the β curve in Fig. 2, one can see a noticeable local increase of the absolute values of this angle at the above-mentioned antipodal positions. The corresponding brightening was also identified on the X-ray images obtained by the Normal Incidence X-ray Telescope (NIXT) in the Fe XVI 63.7 Å line two and a half hours prior to the July 11, 1991 eclipse (Golub and Pasachoff, 1997).

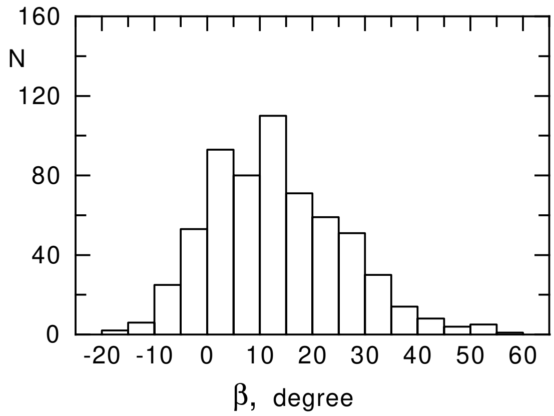

Figure 3. The histogram of distribution of the β angles representing deviations of the plane of polarization (magnetic vector) from the radial direction.

We constructed a histogram of the distribution of the deviation angles of the plane of polarization from the radial direction (Fig. 3). The histogram was constructed for all points inside a ring of width 0.03 $R_\odot$ situated at 1.2 $R_\odot$ from the disk centre. In most cases, β is fairly small, the same as it is in Picat et al. (1979) and Arnaud (1982). Fig. 3 shows that the whole histogram is clearly shifted towards positive β – almost 85% of the points have the positive β angle. The distribution of β, as a whole, may be satisfactorily described by the normal law of distribution, but shifted with its centre at about $+15°$.

In addition, we have constructed two separate histograms for the points with large ($p \geq 10\%$) and small ($p \leq 10\%$) degrees of polarization. As seen in Fig. 4, these histograms are completely different. The first one (Fig. 4a) can be sufficiently well fitted by the shifted normal law of distribution, the mean value of β being 8°. The second histogram (Fig. 4b) is non-symmetrical and differs essentially from the normal distribution. In the region of large β (exceeding 30°),

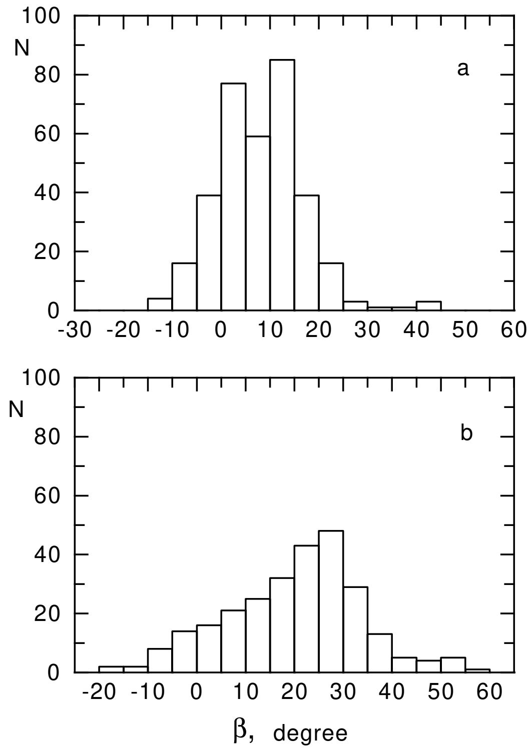

Figure 4. Distribution of the deviation angles β from the radial direction (a) for the points with large p ($p > 10\%$) and (b) for the points with small p.

the number of points abruptly decreases; i.e., the right wing of the histogram is considerably lower than the left one. Therefore, it may be concluded that the relationship between the degree of polarization p and the angle β is quite different in the regions of large and small polarization. Below, we discuss this difference in more detail when analyzing Fig. 5a.

A very interesting peculiarity of the angles β can be deduced from Figs. 3 and 4. Since those angles are basically positive, it means that the magnetic vector almost everywhere deviates from the radial direction clockwise (i.e., against the sense of increase of the position angle). Small parts of the limb where the magnetic vector slightly deviates in the opposite direction (represented by small negative values of β, see also Fig. 2) are situated at about 130° and 310° of the position angle. This is where the axis of the principal magnetic dipole in the Sun was located during the 11 July 1991 eclipse. This fact may be of great importance when considering the general problem of the generation of the green line polarization.

Table 1. The list of the coronal structures under investigation.

No.	Structural feature	Position angle	Symbol in Figures
1	Coronal condensation	67–80	Open Circle
2	Coronal condensation	108–115	Star(*)
3	Coronal condensation	241–258	Cross(x)
4	Coronal condensation	272–287	Solid Circle
5	Equatorial region	84–107	Open Up Triangle
6	Equatorial region	119–129	Open Square
7	Equatorial region	259–268	Solid Square
8	NE–streamer	20–56	Open Down Triangle
9	SW–streamers	162–226	Solid Down Triangle
10	S coronal hole	133–138, 152–158	Solid Up Triangle
11	N coronal hole	313–317	Cross(+) inside Open Circle

3. Analysis of polarization in different large-scale coronal structures

The relations between p, I_λ and β in individual coronal structures are analyzed below in more detail. Badalyan and Sýkora (2001) described anticorrelation between the polarization and the green line intensity for a number of individual coronal structures. The objects that we classified and studied are listed in Table 1. Here, we use the system of the position angles P, corresponding to the north pole position as plotted in Fig. 1. We adopt the term "coronal hole" somewhat conditionally bearing in mind, in fact, the close surroundings of the real coronal holes (the central parts of coronal holes are absent because of the method applied to eliminate the white-light contribution from the eclipse "monochromatic" images). In Table 1, we give the same symbols as are used below in Fig. 5 to identify the individual coronal objects. The present study, the same as in Badalyan et al. (1999a), has been done using smoothed matrices 200×200 pixels (i.e., one pixel of the smoothed matrix corresponding to about $\sim 15''$ on the Sun) with the aim of reducing the statistical scattering of points on the diagrams. Again, the basic investigation was performed for the points inside a ring 0.03 $R_\odot$ wide at a mean distance of 1.2 $R_\odot$ from the solar disk.

In the lower part of Fig. 1, the distribution of the coronal green line brightness in relative units (coronal contour) as measured at the distance 1.2 $R_\odot$ is plotted according to Badalyan and Sýkora (1997a). The same figure shows the intervals of the position angles in which the chosen individual structures and marked by the corresponding symbols are located.

Fig. 5b illustrates a close relation between β and the degree of polarization p for all the eleven coronal objects listed in Table 1. The angles β are mostly positive for all the objects. It should be emphasized that the diagram in Fig. 5a demonstrates a cluster-like character of the distribution of the points: the points related to the individual coronal structures under examination create separated,

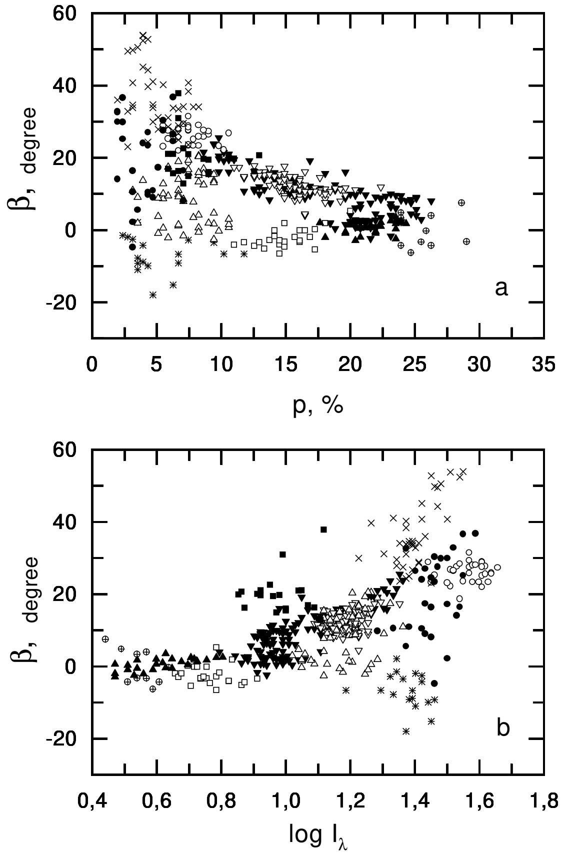

Figure 5. The relationship between the degree of polarization p and (a) the green line intensity I_λ, and (b) the deviation angle β of the plane of polarization from the radial direction for different large-scale coronal structures (see Table 1).

more or less compact clouds. The features characterized by large polarization (vicinities of coronal holes, streamers, part of the equatorial regions of moderate activity) have typically small angles β. In the high-latitude streamers, β is found to range from about $0°$ to $+20°$; in the area surrounding the coronal holes, this interval reduces to $+3°$–$-5°$. When proceeding to the brighter features (equatorial coronal condensations), i.e. considering the features with progressively smaller polarizations, β increases substantially, reaching $50 - -55°$ in some bright regions in the corona. In the general course of the relationship between β and p, one should note a considerable increase of the dispersion of β at small polarizations. The dispersion is not connected, however, with larger scattering of β in the individual features. In fact, in this region of small p, the mean values of β corresponding to the individual large-scale features (in this case, to the bright coronal condensations) differ much stronger than in the region of large p.

The relation of β to the green line intensity I_λ is displayed in Fig. 5b. In agreement with the p–I_λ anticorrelation diagram (see Badalyan et. al, 1999a) and taking into account Fig. 5a, the magnitudes of β increase as the line intensity grows and the degree of polarization decreases.

4. Conclusions

In this paper, we analyze the direction of the plane of polarization in the coronal green line on the basis of observations carried out during the 11 July 1991 solar eclipse. In the eclipse corona under consideration, it was possible to isolate and analyze different large-scale features, which allowed us to draw some original conclusions:

1) The plane of polarization (magnetic vector) significantly deviates from the radial direction. This deviation (angle β) inversely depends on the degree of polarization p: in the regions with large p the angles β are small and *vice versa*. At the same time, fairly smooth large-scale variations of these quantities are observed along the solar limb.

2) The large-scale structures of the 11 July 1991 corona characterized by a high degree of polarization and small β are primarily represented by the huge large-scale streamers and also by the surroundings of the coronal holes and the equatorial regions of moderate activity. The large magnitudes of β (and, correspondingly, the relatively low degrees of polarization p) are found in the coronal condensations above the active regions and are observed on the eclipse day at the antipodal points of the east and west limbs at the latitudes $\pm 20°$. Within these condensations, the β angles manifest a large dispersion due to the large difference between the mean β values in different structures.

3) The points on the β–p and β–I_λ diagrams related to the identified large-scale coronal structures form more or less compact individual "clouds". This fact doesn't seem to be trivial and suggests a relationship between the polarization characteristics and the physical parameters of the individual coronal objects.

4) The histogram of distribution of β is distinctly shifted towards positive angles. At the same time, the distributions of β resemble the normal distribution with the mean value shifted by about $+15°$. The separate histograms constructed for the points with large (larger than 10%) and small p are conspicuously different. While the first one is well fitted by the normal law of distribution shifted to the positive values by about 8°, the second histogram is strongly asymmetrical, the wing of the high degrees of polarization being considerably lower than the wing of small values.

5) The fact that β is mostly positive means that the magnetic vector deviates clockwise from the radius almost everywhere. The small regions at the limb where the magnetic vector slightly deviates in the opposite direction are situated

in the vicinity of the position angles 130° and 310°, i.e., where the axis of the main dipole of the magnetic field was located on the eclipse day of 11 July 1991.

The results obtained can hardly be explained by any mechanisms that do not involve the magnetic field. The study carried out by Badalyan et al. (2002) convincingly proves the close relationship of the green line polarization parameters in different large-scale coronal structures with the strength of the coronal magnetic field and with some arbitrary magnetic field indices. This offers an opportunity to investigate the coronal magnetic field by studying the polarized radiation of the coronal emission lines.

As long as the existing theory of the origin of polarization in the coronal green line strongly contradicts the observational results, the theoretical concept, apparently, needs a revision. It is well known that the degree of the green line polarization depends on the ratio between the line components due to excitation by electron collisions and by scattering of the photospheric photons. At the same time, it is traditionally assumed that only the second component is polarized. This is true, however, only in the absence of directional electron motions in the corona, i.e., of electric currents. It is probably by renouncing this assumption that the contradiction between theory and observations can be resolved. The results of the present study may be helpful in future consideration of the problem.

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