# Some comments on the direction of polarization in the coronal green line

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**Abstract.** The main results of polarization observations in the 530.3 nm coronal line on July 11, 1991 are discussed. A serious contradiction is revealed between the observations and currently accepted theories; i.e., the radial direction of the polarization vector (electric vector in the wave) predicted theoretically does not agree with the experimental results. The direction of polarization in the green line turns out to be tangential, i.e., the same as in the white-light corona, virtually everywhere except in the bright equatorial regions. The analysis of data obtained by other authors does not provide reliable corroboration of the theory. The conclusions drawn in our work urge that further observational studies be carried out and/or an euristic theoretical approach be conceived.

**Key words:** coronal green line – polarization – contradiction between theory and observations

## 1. Introduction

Polarization observations in the coronal green line $\lambda$ 530.0 nm Fe XIV are a valuable source of information on the physical conditions in the lower corona regions with a prevailing temperature of $T \sim 2$ MK. It is particularly important that the study of green-line polarization brings us to the point of understanding the problem of coronal magnetic fields, including the weak ones, which are so far inaccessible to direct measurements.

It is well known that polarization observations in the emission lines are extremely complicated. Therefore, very scarce reliable data on green-line polarization are available nowadays, especially those providing the distribution of the degree of polarization $p$ over a more or less extensive area in the corona. For example, we can cite the paper by Hyder et al. (1968), who obtained the degrees of polarization from 2% to 25% at a distance up to $\rho = 1.5\, R_{\odot}$, separately in a streamer and coronal condensation. During the eclipse of June 30, 1973, Picat et al. (1979) obtained images of a sector of $\sim 80°$ in the corona with three positions of the polaroid. These authors found higher degrees of polarization than Hyder et al. (1968). And finally, Arnaud (1977, 1982, 1984) carried out a few series of observations with an out-eclipse coronograph-polarimeter and obtained lower degrees of polarization.

Successful polarization observations carried out by J.Sýkora (Rušin et al., 1992; Sýkora et al., 1994) during the total solar eclipse of July 11, 1991, revealed some new regularities in the behaviour of the polarization characteristics in the line $\lambda$530.3 nm. However, when processing these high-quality observational data, we ran into a problem of general physics: the polarization plane of the magnetic dipole emission in the line proved to have the same direction as that of the electric dipole emission in the white light.

All attempts to explain this fact by some observational errors failed. It should be noted that the observational material under consideration is unique in itself and has no equal in reliability and completeness. In the context of the problem mentioned above, we shall give a brief description of this data here, emphasizing the high quality and careful processing of the observations. Analysis shows their inherent consistency and agreement with conclusions made by other authors.

On the other hand, the present-day theories (Charvin, 1965; Sahal-Bréchot, 1974; House et al., 1982; Lin and Casini, 2000; see also calculations in Badalyan et al., 2001) assert quite confidently that the direction of polarization in green line must be perpendicular to the direction $p$ in the white light. The cause for such a striking discrepancy between the generally accepted theory and observations is not clear. It is quite possible that our understanding of the process of polarization in the line under discussion will need fundamental revision.

## 2. Results of polarization observations of the eclipse of July 11, 1991

### 2.1. Observational data

The solar eclipse of July 11, 1991 occurred under excellent weather conditions, and its full phase lasted $\approx$6.5 minutes. During the first half of the full phase, a series of four images of the corona in $\lambda\,530.3$ nm were obtained at an exposure of 30 s and successive rotation of the polaroid by 45°. For that purpose, a narrow-band ($\Delta\lambda = 0.17$ nm) interference filter 002FC10-50 with temperature control (Andover Corporation production, USA) was used. In the second half of the full phase, three series of white-light images (four images in each series) were obtained with the same instrument without the narrow-band filter, at exposure times of 1/125, 1/15, and 1 s. The diameter of the Sun in all pictures was $\approx$ 20 mm.

Both green-line and white-light images were photometrically processed in a similar way, their spatial identification being carefully preserved to the accuracy of one pixel. The size of a pixel was 50 $\mu$m, which corresponded to $4.5''$ in the Sun. The white-light images were identified by bringing together the prominences at the western and eastern limbs of the corona of July 11, 1991. The green-line images were identified with one another and with the white-light pictures by making them coincide in the characteristic details well identifiable in all pictures.

The matrices obtained were used to calculate the emission intensity and the degree and direction of polarization in the white light and green line. To determine the green-line polarization parameters, we subtracted the contribution of the white light which passed through the narrow-band filter. For this purpose, we used white-light images and assumed all emission over the northern polar hole to belong to the white-light corona. The subtraction was made separately for every position of the polaroid. The calculations show that the green-line polarization parameters do not change significantly after the white-light contribution is subtracted. Note also that, in doing so, we reduce the effects of sky polarization and stray light. The data processing and subtraction of the white-light are described in detail by Badalyan and Sýkora (1997a) and Badalyan et al. (1997a).

### 2.2. Basic results

A careful processing of high-quality observational data allowed us to construct polarization maps for the entire inner corona of July 11, 1991 (Badalyan and Sýkora, 1997a; Badalyan et al., 1997a).

A well-known peculiarity of that corona was its unusual shape with giant high-latitude streamer systems. At the same time, the coronal condensations, not too bright on the day of the eclipse, were situated on the limb outside the streamer areas. In addition, two regions of decreased radiation of the type of coronal holes were observed. Such an advantageous position of various large-scale structures allowed us to study the polarization parameters in each of them separately.

Our polarization maps reveal the following regularities in the behaviour of the degree of polarization in the green line: 1) polarization is usually smaller in the equatorial than in the high-latitude streamer zones; 2) the degree of polarization grows with height at all position angles. The gradient of this increase is larger in the streamers than at the equator; 3) the degree of polarization in the brightest coronal condensations does not exceed 5%. In the equatorial regions, we, apparently, observed the upper parts of the bright coronal condensations, while their lower parts were occulted by the Moon, whose visible size exceeded significantly that of the Sun during the long-lasting eclipse of July 11, 1991. All these conclusions agree with the previous results. The degrees of polarization $p$ obtained in our study exceed the values reported by Hyder et al. (1968) and Arnaud (1977, 1982, 1984), but are very close to the results of Picat et al. (1979). A comparison of our results with those obtained by other authors is made in Badalyan and Sýkora (1997b) and Badalyan et al. (1997a).

The polarization maps clearly reveal anticorrelation (i.e., negative correlation) between the degree of polarization $p$ and line intensity $I_\lambda$. This effect manifests itself in a peculiar way when we eliminate the dependence of $p$ and $I_\lambda$ on distance, i.e., for the points at a fixed distance from the limb (Badalyan et al. 1999a, Badalyan and Sýkora, 2001). The $p$–$\log I_\lambda$ diagram displays two anti-correlation branches with a space between them where the points are absent. The upper branch corresponds to the high-latitude streamers and the lower one, to the equatorial coronal condensations of different brightness. The branches consist of the clouds of points (clusters) pertaining to isolated structures in the corona, each branch corresponding to the structures of one specific type.

A similar cluster structure is readily seen in all other diagrams where the three polarization parameters (line intensity and degree and direction of polarization) are compared with each other as well as with the magnetic field intensity and components (Badalyan et al., 1999b, 2002a,b). It shows that the polarization characteristics are sensitive to the large-scale coronal structures and configuration of magnetic fields.

Thus, we can draw a conclusion that the observations provide certain realistic information on different physical conditions (including magnetic field) in the large-scale coronal structures. All our results fit within a single self-consistent picture and agree with the distribution of the degrees of polarization reported in literature.

## 3. Direction of polarization in the green line

### 3.1. The essence of the problem

By the direction of polarization, we understand the direction of predominant oscillations of the electric vector in the electromagnetic wave. Note that, earlier, various authors used the term "polarization plane", i.e., the direction of oscillations of the magnetic vector, which is perpendicular to the plane of oscillations of the electric vector.

It should be emphasized that all formulas used to find angles in polarization observations yield the direction of the magnetic vector (Fessenkoff, 1935; Saito and Yamashita, 1962; Billings, 1966). When using these formulas in polarization studies of the white-light corona, one doesn't need doubt the direction of which vector (magnetic or electric) is obtained, since it is well known that the electric vector at Thomson scattering must be tangential. See, for example, Fig. 1 in Kulidzhanishvili et al. (1994), which represents observations of the white-light corona. In spite of the radial direction shown in the figure, it is clear that the magnetic vector is the case in point. However, this problem should be handled with caution when the polarization in line is dealt with.

An important advantage of the eclipse observations of July 11, 1991 was that the green and white-light images of the corona were obtained with the same instrument. The polarization parameters in the white light and green line were determined using the formulas from Saito and Yamashita (1962). The degrees and direction of polarization in the white light obtained in our experiment (see

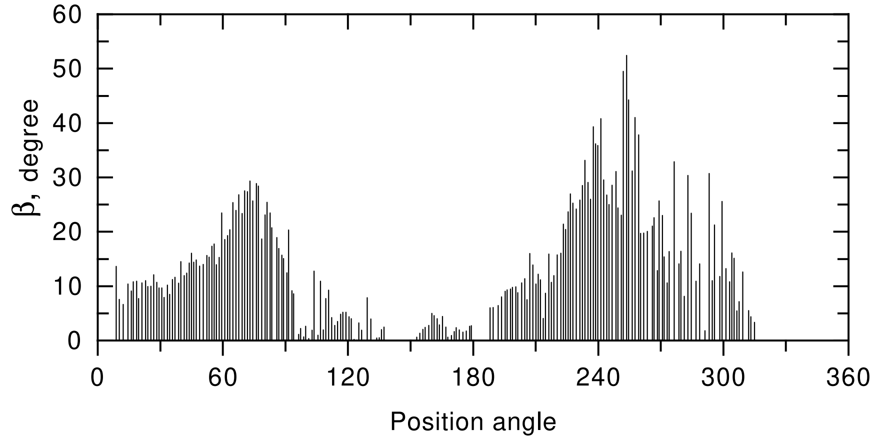


**Figure 1.** The change of deviation (angle $\beta$) from the radial direction of polarization when moving along the limb. The size of the vertical bars corresponds to the values of $\beta$.

Badalyan et al., 1997b) agree perfectly with the results reported by other authors. Therefore, finding the direction of white-light polarization in our study can be regarded as a test for the reliability of the observational data and the correctness of the calculated polarization characteristics.

When determining the direction of polarization in the green line using the formulas mentioned above, we ran into serious difficulties. We found out (Badalyan and Sýkora., 1997a; Badalyan et al., 1999b) that the polarization in high-latitude streamers was nearly tangential. In the low-latitude active regions, the electric vector proved to deviate from the tangential direction by an angle reaching $\beta \sim 40 - 45^\circ$ at some points in the corona (Fig. 1). These results strongly disagree with the general opinion that the preferable direction of polarization in the green line is radial. This opinion is mainly based on theoretical calculations, though it is believed to have empirical corroboration.

In this context, we shall consider some examples from literature to show that no reliable empirical evidence is actually available to support the theoretical concept of the direction of polarization in the green line.

### 3.2. Analysis of literature

B.Lyot was the first to determine the direction of polarization in the green line. There are some references in scientific literature (Charvin, 1965; Hyder et al., 1968) to unpublished data of his visual observations, where he claimed that the direction of polarization in the green line differed from that in the white light. Note that Lyot used an out-eclipse coronograph, which only allowed the observation of bright equatorial regions. In these regions, we also recorded the direction of polarization departing significantly from tangential.

Picat et al. (1979) apply the formulas similar to those given by Billings (1966, p. 96), which, naturally, yield the direction of the magnetic vector. They, nevertheless, assert in their paper that the angle calculated by these formulas determines the direction of the electric vector. Thus, in spite of the conclusion that theory agrees with observations, made by Picat et al. (1979), we believe that their Fig. 4 shows the radial direction of the magnetic vector, which corroborates our results. It should be emphasized that the technique of acquiring observational data and making allowance for the white-light contribution was basically the same in Picat et al. (1979) and in our experiment. The results obtained are also similar. The distribution of polarization obtained by Picat et al. (1979) and by ourselves are represented in Fig. 2. The histograms in Fig. 3 illustrate the deviation of the electric vector from the tangential direction (angle $\beta$).

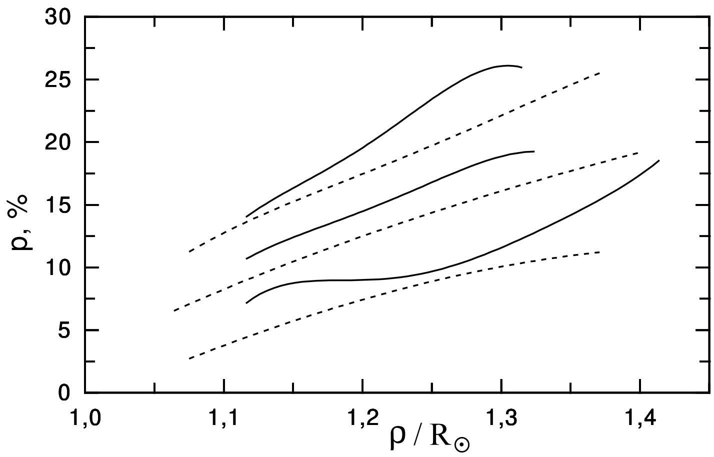


**Figure 2.** Comparison between the green line polarization found by Badalyan and Sýkora (1997) (solid lines) and Picat et al. (1979) (dashed lines). The lower pair of curves relates to equatorial regions, the upper pair of curves relates to streamers (polar regions in Picat et al., 1979); the dashed curve here being calculated from the low and mean curves in Fig. 6 in Picat et al. (1979). The middle curves represent mean values of $p$.

A similar mistake was made by Eddy et al. (1973) when determining the degree of polarization in the infrared line Fe XIII from eclipse observations. They also used formulas yielding the direction of the magnetic, rather than the electric vector.

The conclusions drawn by Hyder et al. (1968) raise doubt for the following reason. Fig. 9 in their paper shows the radial direction of polarization not corrected for the white light contribution. The solid contour circumscribes the regions where the green-line luminosity is quite bright. We can readily see that the direction of polarization does not actually change as we go beyond the solid line to higher and/or weaker regions, where the contribution of the white-light corona significantly increases and should noticeably affect the direction of polarization in the integral (line plus continuum) emission approximating it to tangential.

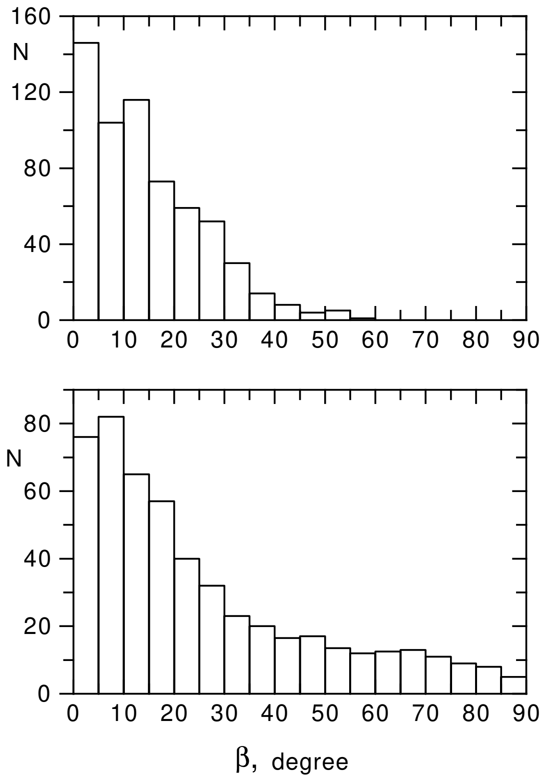


**Figure 3.** Histograms representing distributions of the deviation angle $\beta$ from Badalyan et al. (1999b) (upper panel) and Picat et al. (1979) (lower panel).

Various studies are known where the degree of polarization in the forbidden coronal lines is determined by out-eclipse methods (Arnaud, 1977, 1982, 1984; Querfeld, 1977). For the green line, they yield small $p$ and actually a radial direction of polarization. Transition from the tangential to the radial direction of polarization is due to the change of sign of the second Stokes parameter $Q$. This parameters is calculated as $Q_\lambda = Q - Q_{wl}$, where $Q$ corresponds to the integral emission in the line plus continuum passed through the narrow-band filter, while $Q_\lambda$ and $Q_{wl}$ correspond to the line and continuum, respectively. To precisely determine the sign of $Q_\lambda$, we must, obviously, take into account the contribution of the white light to the integral emission. However, the reliability of the estimation of this contribution in the papers cited above raises serious doubts. In fact, we could not find publications analyzing the total passbands of the respective filters (including their far wings). Instead, all authors indicate the halfwidths of the filters. As a result, one is unable to tell how accurately the sign of $Q_\lambda$ (and, hence, of the line polarization) was determined. On the contrary, an opposite example can be cited. Describing observations in the forbidden line Fe XIII 1074.7 nm, Querfeld compared the intensities in the line and in the white light which would have passed through a filter of the same halfwidth as used to find the integral line+continuum emission ("line" channel) (see Table II in Querfeld, 1977). As seen from the table, the last value was obtained by dividing by 4 the intensity of the white light measured in the "white-light" channel after having passed through a filter with a halfwidth four times as large as that in the "line" channel. Thus, it is very likely that the authors used halfwidths of the filters in their calculations and, therefore, did not adequately allow for the white-light contribution.

### 3.3. Advantages of our observations

Therefore, analysis shows that all previous conclusions about the radial direction of polarization in the green line are questionable.

Let us summarize the advantages of our data. Observations of the corona on July 11, 1991, carried out by J. Sýkora, were the first to yield the green-line polarization in the entire inner corona during a total solar eclipse. The images are of very good quality and have rather high spatial resolution. The polarization images of the white-light corona obtained with the same instrument made it possible to check up the application of formulas for determining the direction of polarization. The fact is that many well-known formulas define the tangent of the double angle, so that the signs of the corresponding sines and cosines must be determined with certainty. Thus, the white-light corona, where the direction of polarization is known exactly, provides a good opportunity for test calculations.

There are some important points that should be noted. In observations with a Stokes polarimeter, the white-light polarization is taken into account by subtracting the polarization signals. As a result, the white-light contribution may be both underestimated and overestimated. In order to avoid it, we subtracted the white-light intensities obtained from polarization images of the white-light corona, separately for each of the four positions of the polaroid. With the assumption that actually all emission over the northern coronal hole belongs to the continuum, it reduces the maximum possible correction for the white-light contribution. In other words, the intensity values obtained after subtracting can not be negative. We also made test calculations significantly increasing the subtracted white-light intensities proportionally for all positions of the polaroid. This procedure, naturally, reduces the coronal regions, where the polarization can be calculated. Nevertheless, it does not actually change the direction of polarization in the high-latitude streamers, which remains tangential, i.e., the same as in the white light observations.

Thus, we believe that the problem of determining the direction of polarization in the green line from observations still remains unsolved. There are strong reasons to doubt that previous observations provided convincing evidence for the agreement between theory and observations. Moreover, our observations are more reliable in some important points than the earlier ones.

## 4. Conclusion

When processing the observations of July 11, 1991, we found that high degrees of polarization in streamers corresponded to nearly the tangential rather than the radial direction $p$. This result is in apparent contradiction with theoretical conjectures. The analysis of observational data available in literature brings us to the conclusion that no reliable observational evidence exists to date to support the theoretical postulate that the directions of polarization in the white light and green line must be mutually perpendicular.

Our results show that the polarization parameters in the green line are sensitive both to the structure of the emitting regions and to the magnetic field strength and components, i.e., to the magnetic field topology in the corona. Thus, we hope that polarization observations of the green corona may be used for full diagnostics of the coronal plasma, including the magnetic field. However, the contradiction with the generally accepted theory discussed above does not allow its use to derive information on magnetic fields in the solar corona.

In our opinion, the task of resolving this contradiction is twofold. First, new high-precision observations of polarization in the green line should be done all over the corona. They will corroborate or disprove the results of our observations of July 11, 1991. On the other hand, the theoretical analysis of the problem should, obviously, use a new euristic approach. Here, we see various possibilities. For example, the polarization plane may, for some reason, turn by 90° compared to its theoretical direction. A certain mechanism may exist that converts the magneto-dipole emission to the magneto-electric one, i.e., the same as in the Thomson scattering. And finally, we should probably take into account the polarization of the green-corona emission component produced by electron collisions, which was traditionally considered unpolarized.

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