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Polarization of the green-line corona on July 11, 1991 solar eclipse

O.G. Badalyan[1] **and J. Sýkora**[2]

[1] Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, 142092 Troitsk, Russia
[2] Astronomical Institute, 05960 Tatranská Lomnica, Slovak Republic

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Abstract. High quality photographic polarized images of the green-line λ530.3 nm corona were obtained during the July 11, 1991 solar eclipse by using a narrow-band 0.17 nm interference filter. Image processing allowed us to derive the green-line polarization within the range 1.08 - 1.40 $R_\odot$. The corresponding degrees of polarization p vary from 0% up to about 30% in different coronal regions. At equatorial latitudes p varies from 0% to 15%, while in the brightest coronal regions it does not exceed 5%. In regions of observed high-latitude white-light coronal streamers, the green-line polarization gradually increases with distance from 10% to about 30%. Anticorrelation between the degree of polarization and the green-line corona intensity was found in analysing the entire data matrix. It seems that this finding in itself contains information about the role of electron collisions in the excitation of the green line, and about certain physical properties of the coronal magnetic field.

Key words: polarization – eclipses – Sun: corona; magnetic fields

1. Introduction

The question of polarization of the 530.3 nm FeXIV coronal line remains insufficiently solved, regardless of the large number of experimental and theoretical investigations devoted to this problem. Electron collisions and photo-excitation (process of absorption of the photospheric radiation) represent the basic mechanisms of excitation of this forbidden line. The relative contribution of these mechanisms depends of a number of parameters, in particular of the heliocentric distance.

Photo-ionization and the subsequent emission of photons, i.e. resonance scattering, lead to the appearance of linear polarization due to the anisotropy of photospheric radiation. The theoretical asymptotic limit of the green-line degree of polarization, assuming collisions are negligible and without considering the line-of-sight integration, was found to be 0.43 for a radial magnetic field (see, for example, House 1974). It is clear, however, that this very theoretical degree of polarization is reduced by a number of factors. First of all, the radiation seen by an observer represents an integral along the line of sight. This causes a certain decrease of the resulting polarization. Besides, electron collisions exciting the upper sublevel of the ground configuration and also the higher levels of ion FeXIV, do not contribute to the polarization of the green-line radiation. And, finally, in the presence of magnetic field, the depolarizing collisions (transitions between different magnetic sublevels which equilibrate populations of the sublevels) and the van Vleck effect complete the above-mentioned factors.

Depending of the contribution of photo-excitation relative to electron collisions, and depending of the strength and configuration of the magnetic field, the maximum linear green-line polarization can be substantially lower than 0.43. For example, in the case of the House et al. (1982) model of the dipolar solar magnetic field, the polarization of the green-line corona at 2 $R_\odot$ should theoretically be only 0.20 near to the solar equator, 0.05 – 0.15 at middle latitudes and the poles, and should be practically 0.00 at 70.5° due to the van Vleck effect. It should be mentioned that the effect of magnetic field is also manifested by the change of the direction of the plane of polarization of the resulting radiation. Thus, the polarization, together with the intensity of the green line, contain very valuable information about the coronal magnetic field. Particularly, direction of the plane of polarization corresponds to direction of the magnetic lines of force.

A number of highly dispersed results of green-line polarization were obtained by means of the out-eclipse coronagraphs, during the solar eclipses and aboard satellites. The coronagraphs usually yielded a very low degree of polarization - mostly from 1% to a few % (Arnaud 1982; Querfeld & Smartt 1984), while eclipse observations displayed a large scatter of the measured polarizations: for example, 0% (Beckers & Wagner 1971); from 5% to 20% (Picat et al. 1979); about 30% (Mogilevskij et al. 1973). Satellite observations (for example, the coronagraph/polarimeter experiment on board SMM, House et al. 1981) are rather sensitive and uncertain due to the problem of calibration.

The application of high-quality narrow-band filters now make it possible to observe polarization simultaneously

Send offprint requests to: J. Sýkora

throughout the whole solar corona (in contradiction, for example, to spectral measurements). Beginning with the June 30, 1973 eclipse observation, one of us (J.S.), has gradually improved this method to a reliable technical state. Especially the last observation, carried out during the 1991 eclipse, seems to be of very good quality.

2. Experiment and observation

The observation was carried out on July 11, 1991 at $18^h\ 48^m - 18^h\ 54^m$ UT in Mexico, Baja California, La Paz ($\lambda = -110°$ 15' 27", ϕ = +24° 09' 24", h = 10 m) under excellent weather conditions. An achromatic Zeiss refractor, 130 mm in diameter and 1950 mm in focal length was used to realize the experiment. An ultra-narrow-band 0.17 nm tunable image quality interference filter 002FC10-50 with a temperature control (produced by the Andover Corp., USA) was fitted at the eye-piece end of the telescope to isolate radiation of the 530.3 nm spectral line. A rotatable polarizer (fixed successively to four positions differing by 45° in orientation of its plane of polarization) was placed just in front of the interference filter. This design with no really reflecting surfaces, suppressed any instrumental polarization which was then, in fact, not measurable.

A sixty-millimetre Kodak Tri-X Pan roll-film was used to record photographic images of the linearly polarized light of the green-line corona. One set of four images was taken with exposures of 30 s during the first half of totality (the whole eclipse lasted almost 6.5 minutes in La Paz). Besides this, three sets (exposures 1/125 s, 1/15 s and 1 s) of four white-light polarized corona pictures were taken. (Our paper on the white-light corona polarization has been submitted for publication (Badalyan et al. 1996)).

All the original negatives were subjected to microdensitometer image processing at the Ondřejov Observatory (Zicha et al. 1992). We chose a 50-micron pixel dimension to record densities. This, about 5 arcsec, resolution was maintained throughout the whole data analysis. Before calculating the intensities, degree and direction of polarization, a crucial requirement had to be fulfilled: as perfect a fitting as possible of the four images of the given set, taken at different positions of the polarizer. We simply had to be sure that physically the same point of the corona was extracted from the corresponding four images for subsequent calculations. This particular procedure was dealt with and realized for us in the Institute of the Problems of Information Transmission in Moscow. The white-light images were relatively easy to identify using well visible prominences at the east and west solar limbs. Subsequently, the green-line images were identified using common characteristic structural details seen both in the green-line and white-light corona pictures. We have currently achieved one pixel accuracy in the process of identification of the images.

3. Analysis of the observational data

In our case, when the polarizer was successively adjusted to four positions differing by 45°, the calculation of the green corona intensity and of its degree of polarization was performed according to the following formulas (Saito & Yamashita 1962):

$$p = \frac{a^2 - b^2}{a^2 + b^2} = \sqrt{\left(\frac{I_1 - I_3}{I_1 + I_3}\right)^2 + \left(\frac{I_2 - I_4}{I_2 + I_4}\right)^2}, \tag{1}$$

$$I = a^2 + b^2 = I_1 + I_3 = I_2 + I_4, \tag{2}$$

$$\tan 2\alpha = \frac{I_2 - I_4}{I_1 - I_3}. \tag{3}$$

Here a^2 and b^2 are the intensities of the polarized components of radiation, I_k is the intensity at physically the same point of the image with the polarizer in the *k* position. The α-values are defined according to the signs of $\sin 2\alpha$ and $\cos 2\alpha$ in (3).

Obviously, a certain amount of white-light coronal radiation is contained in the green-line images, recorded during the eclipse, and namely the radiation which has passed through the narrow-band filter applied in our experiment. That is why, the degree of polarization, derived immediately by using Eq. (1), is deteriorated to some extent by the polarization of the white-light corona. This influence increases with distance from the solar limb and is particularly evident in the region of the north polar coronal hole. Very low radiation is detected on the green-line images in the region of this hole, but, at the same time, the degree of polarization calculated according to (1) is 30-35%. The comparison of these values with the degree of polarization observed for the white-light corona reveals that both the quantities are practically identical in the north polar region. This fact allows us to assume that over the north polar hole almost all the radiation passing through the interference narrow-band filter comes from the white-light corona and the contribution of the green line itself is negligible in this region. This evaluation and assumption alone enable us to estimate, in general, the effect of the white-light radiation on the measured green-line corona degree of polarization.

In this procedure, we used the measured polarization and the intensity of the white-light corona, as derived from the images taken with an exposure of 1/125 s. First of all, it was necessary to reduce the intensities calculated both for the green-line corona and the white-light corona to a common base of relative units. By comparing the intensities of the white-light corona with the green-line intensities observed in the region of the north polar coronal hole, we have found that logarithms of the white-light corona intensities are for 0.25 higher than the corresponding values for the green-line corona. In other words, to reduce all the intensities to a common relative scale, it was necessary to add the value 0.25 to all the uncorrected values of the green-line intensities observed. In this case the ratio *W* of the purely green-line intensity to the intensity of the white-light radiation is 0.8 over the north pole. Note, that the ratio *W* should be understood as a ratio of the green-line radiation to the white-light corona radiation passing through the narrow-band filter (i.e., to the white-light corona radiation integrated over the whole passband of the filter). On an average, the values of the same ratio are 2.5 - 3.0 in the majority of coronal regions around the sun,

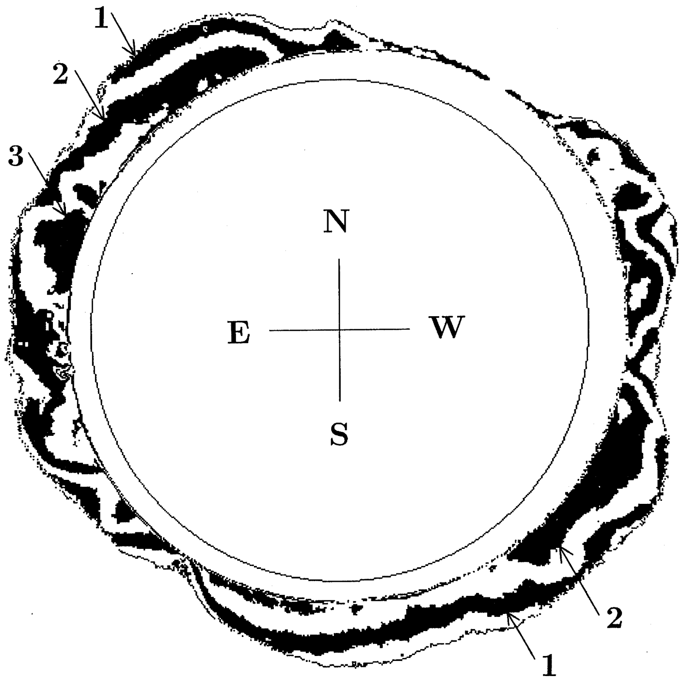

Fig. 1. Ratio W of radiations in the green-line and in the white-light corona passing through the narrow-band filter. Isolines are drawn with step $\Delta logW = 0.15$ and the numbers 1, 2, 3 correspond to $logW = 0.15$, 0.45 and 0.75, respectively

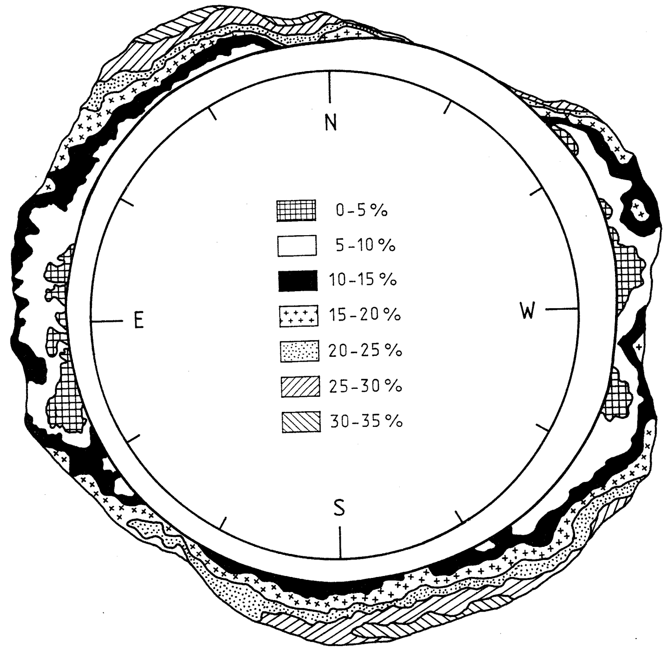

Fig. 2. Distribution of the green-line degree of polarization around the sun

and they even increase up to 8.0 - 9.0 in the brightest regions of the green-line corona (Fig. 1). It should perhaps be mentioned that the visible diameters of the sun and moon differed considerably during the July 11, 1991 long-lasting eclipse. That is why, many of the bright coronal regions situated lower than 1.08 $R_\odot$ at the east limb and 1.15 $R_\odot$ at the west limb were covered by the moon. (The difference between the east and west limbs is due to the green-line images having been taken during the first half of the eclipse totality.)

Since the angles of the direction of polarization of the white-light corona and that of the green-line corona do not generally have to be identical, it would be, in fact, necessary to subtract vectorially the contribution of the white-light corona from the observed polarization of the uncorrected green-line corona. Nevertheless, in our case, we used a different procedure. Since all the intensities measured on the four green-line images and those on the four corresponding white-light images were reduced to a common scale of relative intensities, we were able to subtract immediately a contribution of the white-light radiation separately for each position of the polarizer. The differences $I_{(l,i)} = I_{(l+c,i)} - I_{(c,i)}$ (where indices l and c relate to the line and continuum, respectively, and i denotes the number of the polarizer position) were calculated for each pixel of all the matrices individually. The calculations according to Eqs. (1) – (3) were then repeated – now, however, for the corrected radiation of the green-line corona. This procedure of the linear subtraction of intensities is adequate to the vectorial subtraction of the polarization values. Performed calculations revealed that elimination of the white-light contribution reduces the obtained polarization for about 5%, this effect being more pronounced in the equatorial regions than in the regions of the high-latitude streamers.

The maximum error in p, caused by the photometric processing of the coronal images, does not exceed 3–5%.

4. Results

The final results are shown in Fig. 2, which indicates that:

(a) The polarization in the green coronal line does not exceed 30%.

(b) At low latitudes the degree of polarization is within 0% and 15%. Considerably higher degrees of polarization were found in the regions, where the huge streamers were observed in white-light (on the July 11, 1991 eclipse day they were situated at unusually high latitudes).

(c) The green-line degree of polarization increases with distance from the solar limb. This increase is more distinctly seen in the regions of the high-latitude white-light streamers.

(d) In comparing the distribution of the degree of polarization (Fig. 2) with that of the green-line intensity (Fig. 3), one can see that, in the brightest green-line corona regions near the solar equator, the degree of polarization does not exceed 5% at the heliocentric distances in question. Since the lowest and most dense layers are, of course, covered by the moon in our coronal images, it is quite probable that only the upper parts of the bright coronal condensations can be seen here.

In our opinion, the most interesting fact in Fig. 2 is that the degree of the green-line polarization increases not only with distance from the solar limb but, it also clearly increases from the brightest to the fainter regions of the green-line corona. Con-

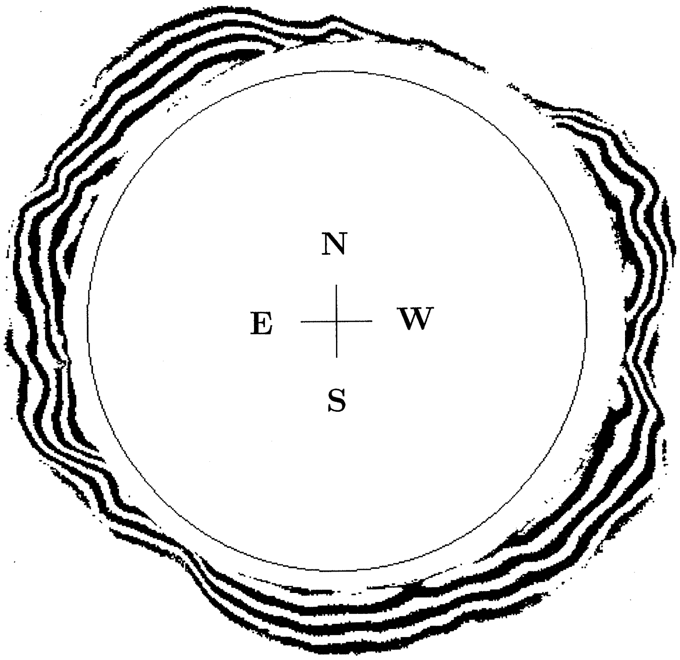

Fig. 3. Isolines of the green-line intensity shown in relative units with step $\Delta logI = 0.15$

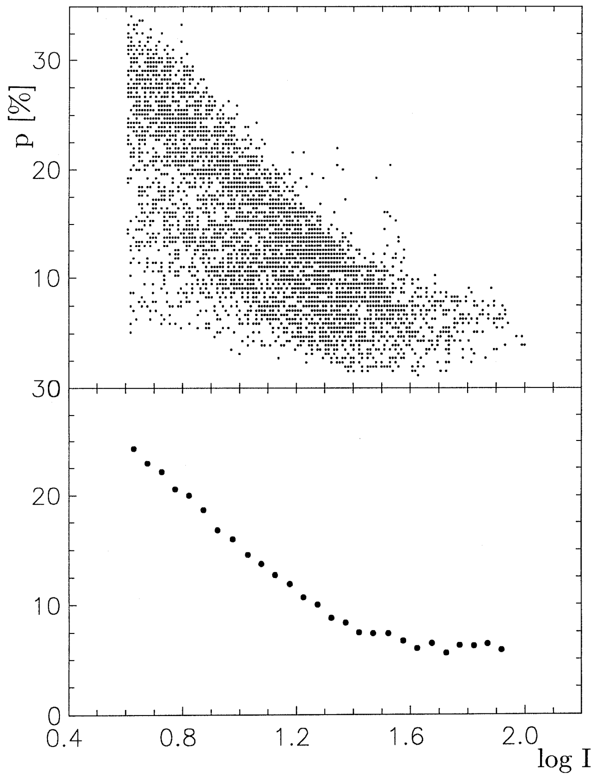

Fig. 4. Upper panel shows anticorrelation between the degree of polarization and intensity of the green-line corona (intensities lower than *log I* = 0.6 were not considered). Lower panel presents averaging performed within intervals $\Delta logI = 0.15$

siderably high degrees of polarization were observed in the regions corresponding to the lower layers of the NE-streamer and the system of the SW-streamers. In these regions the white-light corona is bright, whereas the green-line radiation there is certainly lower as compared with the cluster of loops near the equator. Consequently, Fig. 2 represents a certain indication of anticorrelation between the degree of polarization and intensity of the green-line corona.

We have obtained such a relation for the entire data matrix averaged by 3x3 pixels, i.e. about 15 arcsec resolution was achieved. In all, we have analysed that relation for about 4300 points. In the *p*-versus-*logI* diagram this cluster of points fill a rather broad band with dispersion in *p* ranging from about $\pm 7\%$ (in the low-intensity regions) to about $\pm 5\%$ (see upper panel in Fig. 4). Dispersion of points, seen in this part of Fig. 4, reflects dependence of the degree of polarization on distance from the solar limb, as well as, on position angle (i.e. on the coronal brightness in a given direction). That is why, rather complicated character of anticorrelation between *p* and *I* is displayed. On the other hand, the averaged anticorrelation of *p* and *logI*, shown in the lower part of Fig.4, is considerably smoothed and well-expressed.

Distribution of directions of the plane of polarization (electrical vector) is shown in Fig. 5 at four discrete distances from the sun's limb. It seems that the direction polarization of the green-line corona is mainly tangential in the regions of high-latitudinal streamers (similarly, as found for the 1991 white-light corona by Badalyan et al. 1996). In the equatorial regions one can see deviations from the tangential direction, which apparently suggest an influence of the magnetic field.

5. Discussion

As far as we know, a general distribution of the degree of green-line polarization is derived using high-resolution eclipse observation for the first time. We have determined the degrees of polarization for $R_\odot$ ranging from 1.08 to 1.40. The degrees of polarization observed are considerably lower than the published upper theoretical limit of 0.43, they are between 0% and 30% in different regions of the solar corona. The highest degrees of polarization were observed in the regions where the lowest parts of the white-light NE-streamer and the system of the SW-streamers are situated. In the equatorial regions the degree of polarization varies from 0% to 15%, whereas in the regions of the highest green-line radiation *p* does not exceed 5%.

The anticorrelation between the degree of the green-line polarization and its intensity may indicate that electron collisions contribute considerably to its excitation. If this is the case, then we have a new method of dividing the green-line radiation into two components - one of them being excited by the electron collisions and the other being the consequence of the resonance scattering of photospheric radiation. It is quite possible that the scattering takes place just outside the bright loops, in the background component of the solar corona (Badalyan et al. 1996).

The investigation of the effect of the magnetic field on the measured green-line degree of polarization also seems to be very important. As it is known, theoretical considerations have been

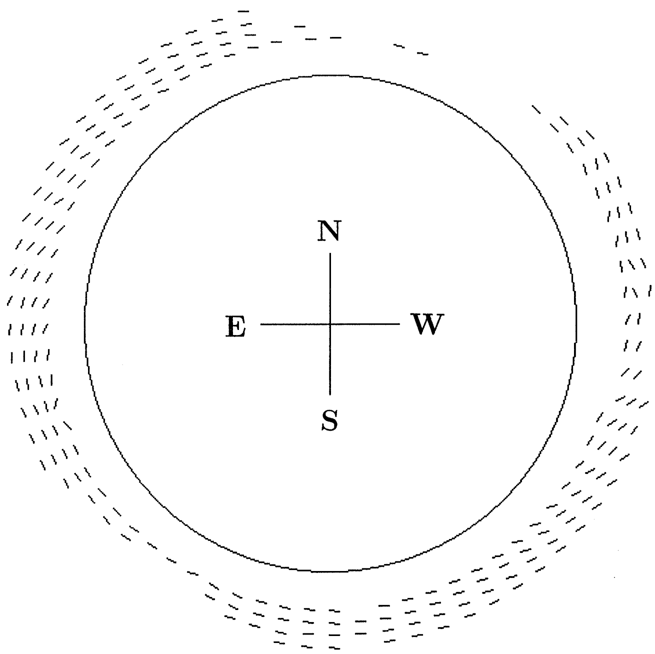

Fig. 5. Directions of the plane of polarization at distances 1.15, 1.20, 1.25 and 1.30 $R_{\odot}$.

carried out for some idealized models only. The conditions in the real corona are far more complicated and a special approach to the problem is necessary (we plan to deal with this matter in the near future).

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