ON THE POLARIZATION OF
THE SOLAR CORONAL EMISSION LINES

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Abstract. The results of the spectrophotometrical measurements of the polarization in the coronal lines Fe xɪv 5303 Å and Fe x 6374 Å are given. Polarization spectrograms were obtained by two spectrographs (prism and echelle types) during the solar eclipse in Mexico on 7 March, 1970 near the region of the second contact at the heights 0.06 to 0.12 $R_\odot$ above the limb. The polarization in the green line is about 30% (for averaged height 1.08 $R_\odot$). The polarization in the red line is close to the errors of the measurement and does not exceed 6%. A brief discussion of the results is also given.

1. Introduction

The aim of this paper is to discuss some results of the investigation of polarization in the emission lines of the solar corona during the total solar eclipse of 7 March 1970. During the total solar eclipse of 30 June 1954 one of the authors obtained the polarization spectrograms of the corona, according to which a great magnitude of polarization was determined both in the green and in the red emission lines (Mogilevsky *et al.*, 1960). This result was not confirmed by later observations (Hyder *et al.*, 1968; Charvin, 1965; Beckers and Wagner, 1970, 1971), which showed that the polarization in the line Fe x 6374 Å was absent (or was less than the experimental error), and the polarization in the line Fe xɪv 5303 Å had a value much less than observed by Mogilevsky *et al.* Moreover, some theoretical considerations showed that the polarization in the red line should be equal to zero if the line excitation was produced by the resonance scattering (Hyder *et al.*, 1968; Charvin, 1964a, b, 1965; House, 1970a, b, 1971, 1972).

During the eclipse of 7 March 1970 in Mexico (near Miahuatlan) new polarization spectrograms of the corona were obtained (Mogilevsky, 1970). We shall consider some of the observational material obtained.

2. Instruments and Observations

Two spectrographs were used to produce polarization spectrograms. They were fed by two horizontal telescopes (coelostats, secondary mirrors, objectives).

The first instrument was the two-prism spectrograph ISP-65, the same as was used for the solar eclipse of 30 June 1954 (Mogilevsky *et al.*, 1960). Its parameters: $D:F= =1:7.4$; $F_{col}=F_{cam}=390$ mm (for 4860 Å). The dispersion changes from 25 Å mm^{-1} in the green part to 140 Å mm^{-1} in the red part of the spectrum. The spectrograph was fed by a mirror objective $D=120$ mm, $F=125$ cm. A Wollaston prism was in-

stalled inside the collimator in such a way that two spectra with the mutually perpendicular direction of the polarization were obtained simultaneously. This method (if one does not make any suppositions about the direction of the polarization) gives only the lower limit of the real value of the polarization, but has an advantage in that it is possible to obtain two spectra corresponding to the same regions of the corona. The angle between the vertical slits of the spectrograph and solar limb at the point of the second contact was $\approx 20°$ (position angle $\approx 35°$). The slit was 0.04 mm wide.

The spectra were photographed on a panchromatic film type A-700. Two pairs of the spectra were obtained with exposure times 20 and 40 sec. In order to determine the total instrumental polarization and for the aim of calibration, the spectra of the solar disk were obtained through the system of the neutral filters and a step wedge on the day before the eclipse near the time of total phase.
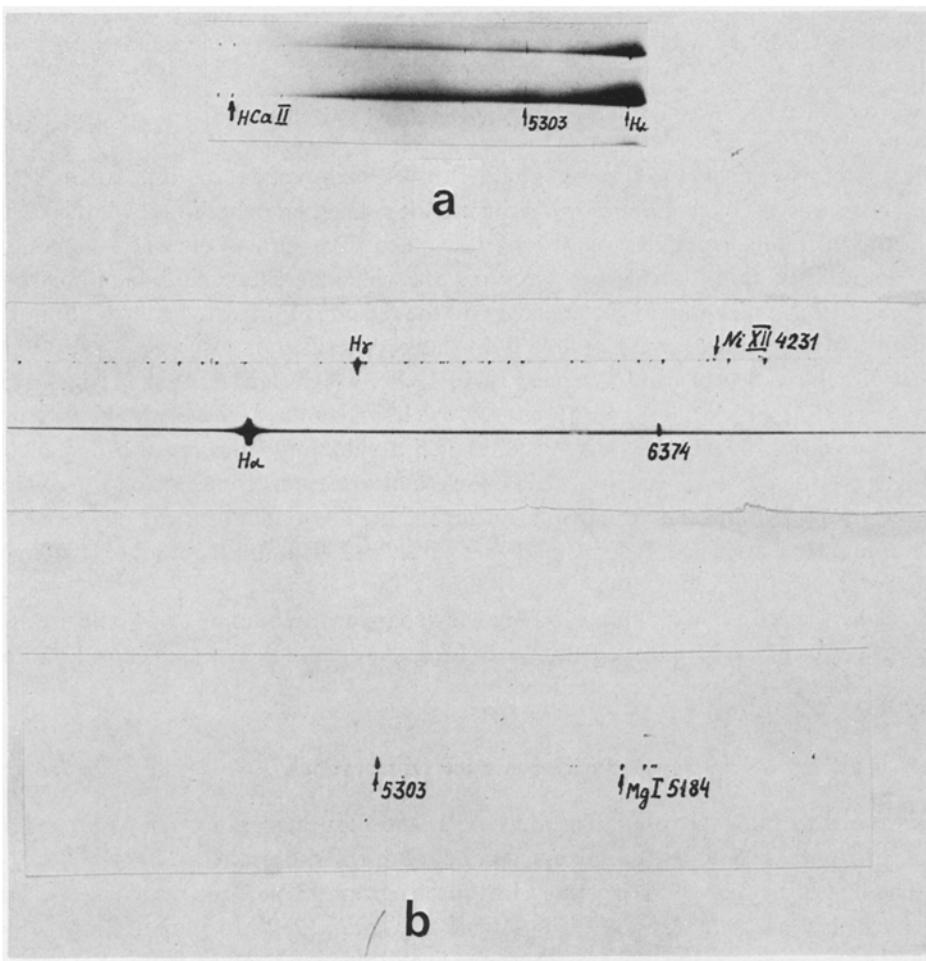
Fig. 1. A negative reproduction of the coronal spectra. (a) Spectrum obtained by two-prism spectrograph; exposure time 20 sec; (b) Two parts of the first 7 sec spectrum near the green and red lines obtained by echelle spectrograph.

The second instrument was an echelle spectrograph type STE-1 with a grating of 600 lines per mm, a 3° prism and $f_{cam} = f_{col} = 980$ mm. Geometric light-gathering power of the instrument was 1:13. It was adopted for the simultaneous recording of three orders (IV, V, VI) in the spectral interval from 3400 to 7000 Å. The dispersion of the spectrograph in different orders varied from 6 to 10 Å mm^{-1}. The achromatic objective with $F = 500$ mm was used. The turnable polaroid was located in front of the spectrograph. The spectrograms were obtained at three positions of the polaroid shifted successively by 120°. Two series of polarization spectrograms were obtained during the total phase with exposure times 7 and 40 sec. The Sun's image at the spectrograph slit was oriented in the same way as for the first spectrograph. The slit was 0.1 mm wide. Calibration procedure was also the same. In Figure 1 one can see the examples of the spectrograms from each instrument. They consist of the lines of a prominence and some coronal lines (including Ni x 6702 Å, Fe x 6374 Å, Fe xiv 5302 Å, Ni xiii 5116 Å, Ni xii 4231 Å, Fe xi 3987 Å).

3. The Account of the Instrumental Polarization

As it has been mentioned above, on the day before the solar eclipse the spectra of the solar disk centre were obtained for the purpose of calibration. The positions of the mirrors and the exposure times were the same as on the next day during the total phase. The whole procedure was also similar, that is the spectra on the echelle spectrograph were obtained at three successive positions of the polaroid and the spectra on the two-prism spectrograph were obtained with the Wollaston prism. Using the spectra we could determine the instrumental polarization in different spectral intervals. All the estimations of the polarization in coronal lines given below were made taking into account the instrumental polarization in the following way.

In the case of two-prism spectrograph the intensity ratio of two spectra α_1 was equal to 1.7 that corresponded to the value of the instrumental polarization $\simeq 26\%$. As the intensities of the spectra lay on the linear part of the characteristic curve, the relative error δ in the determination of these values was 3 to 4%. The polarization value in the coronal lines was determined from the following expression

$$p = \frac{\alpha - \alpha_1}{\alpha + \alpha_1} \pm 8\delta \frac{\alpha_1 \alpha}{(\alpha + \alpha_1)^2}$$

where α is the intensity ratio of two spectra obtained during the total phase, α_1 is the similar value for the calibration spectra, and δ is the relative photometrical error for the intensity measurement of each spectrum. We assumed the value of δ to be approximately the same for all four intensity measurements. One can see that the maximum error equal to 2δ takes place at $\alpha = \alpha_1$, that is when the polarization $P = 0$.

In the case of echelle spectrograph the value and the azimuth of polarization relative to the first position of the polaroid were determined from the following expressions:

$$p = 2 \frac{\sqrt{(1 - \alpha) + \alpha(\alpha - \beta) + \beta(\beta - 1)}}{1 + \alpha + \beta}$$

$$\tan 2\chi = \sqrt{3} \frac{\alpha - \beta}{2 - \alpha - \beta}$$

where α and β are the ratios of intensities of the second and third spectra to the intensity of the first spectrum, corrected for the instrumental polarization. The correction for the instrumental polarization was made by dividing the values α_2 and β_2 obtained during the eclipse by the corresponding values α_1 and β_1 measured from the calibration spectra. In the red region the instrumental values $\alpha_1 = 0.92$ and $\beta_1 = 0.64$, correspond to instrumental values of P and χ equal to 25% and 24° respectively. In the green region $\alpha_1 = 0.94$ and $\beta_1 = 1.29$, while P and χ are equal to 20% and 124° respectively. The expressions for the errors in polarization P and angle χ in the general case are very cumbersome. But as in the first case, the maximum absolute error of the polarization value (supposing that the errors of the particular intensity measurements for all six spectra are the same and equal to δ) is equal to $\simeq 2\delta$, while the maximum error for the χ is $\simeq 20°$. It takes place when the polarization value P is very small.

4. Results

We shall describe the preliminary results of the photometry of the polarization spectrograms in green (Fe XIV 5302 Å) and red (Fe X 6374 Å) emission lines.

In the case of two-prism spectrograph we treat the results obtained from the first (20 sec) frame because of its better quality. Fifteen photometric tracings were made parallel to the dispersion across the green coronal line Fe XIV 5303 Å. The length of the spectrum along the vertical slit is $= 0.18 R_\odot$, where $R_\odot$ is the Sun's radius. The width of the slit of the microphotometer corresponds to 0.17 Å and the height to 10″. The height steps of the photometric tracings were 13″ or 0.013 $R_\odot$. The height of the solar limb was fixed by using the position of the prominence lines with the accuracy $\simeq 0.02 R_\odot$. The height interval covered by the tracings was from 1.03 to 1.1 $R_\odot$. The centre of the spectra coinciding with the well-exposed part of the spectra was located at the height $(1.07 \pm 0.02) R_\odot$. To compare two sets of tracings, belonging to each spectrum, we supposed that the position of maximum intensity in the continuum on every spectrum corresponded to the same place in the corona. The accuracy of that procedure was $\simeq 0.013 R_\odot$. From the photometric tracings the equivalent line-widths were measured and then compared to obtain the polarization (Figure 2). Mean values of the polarization in the line Fe XIV 5303 Å brought to a mean height 1.07 $R_\odot$ was equal to $32 \pm 6\%$. The polarization in the continuum near the green line on the height 1.05 was about $33\% \pm 6\%$.

Unfortunately because of low dispersion in the red region and small intensity of the red line Fe X we could not determine the polarization in this line by the two-prism spectrograph.
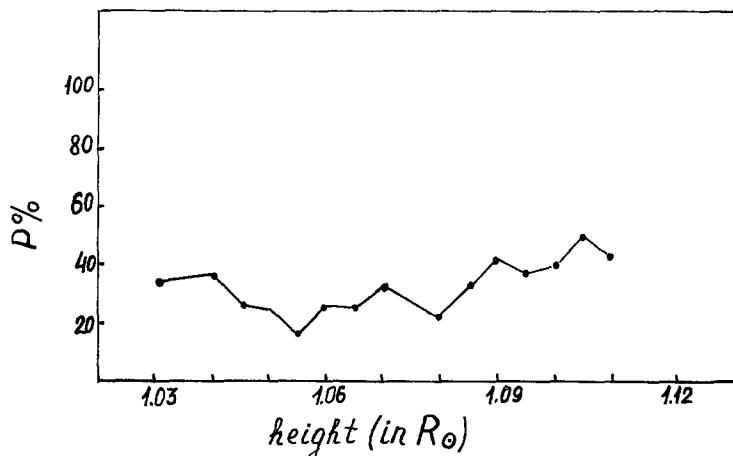
Fig. 2.   The polarization in the green coronal line Fe xiv 5303 Å obtained by
two-prism spectrograph ISP-65.

The spectrograms obtained by the second echelle spectrograph were treated in a similar way. This treatment gave the possibility of determining not only the value, but also the direction of the polarization. We had two series of spectrograms obtained with exposure times 7 and 40 sec. On the 7 sec frame we investigated the polarization only in the red line Fe x 6374 Å, because the continuum near the green line was practically absent on the spectrograms, and the comparison of the spectra in this region could not be made with confidence. This comparison was carried out by identifying the points of maximum intensity in the continuum near the line and by comparing the structural details in the line itself; both methods gave similar (with the accuracy of 0.01 $R_{\odot}$) results. The height above the limb corresponding to the well exposed part of the spectra was in the interval (1.03–1.06) $R_{\odot} \pm 0.02\ R_{\odot}$. In this interval we made four tracings across the red line. The mean value of the polarization in the red line was $\simeq 6 \pm 5\%$, which is comparable with the experimental errors. The variation in the direction of the polarization was very great, therefore there does not exist a reasonable mean value. The polarization in the continuum near the line was about 31% at the height (1.04 $\pm$ 0.02) $R_{\odot}$, and the angle between the polarization plane (electric vector) and the tangent of the limb viewed clockwise, was $\simeq 25\%$.

From the 40 sec exposure spectra we obtained the polarization in both lines. The height interval for the red line, corresponding to well exposed part of the spectra, was (1.05–1.1) $R_{\odot}$. The mean value of the polarization brought to the mean height (1.08 $\pm$ 0.02) $R_{\odot}$ was about 7% $\pm$ 5%. This value is too close to the experimental errors, so we cannot consider it as the evidence of the presence of polarization in the red line. The polarization in the continuum near the red line for the mean height 1.06 $R_{\odot}$ was $\simeq 35\%$; the angle between the electric vector and the tangent to the limb viewed clockwise was $\simeq 40°$.

The height interval for the green line, corresponding to the well exposed part of the spectra, was (1.07–1.12) $R_{\odot}$. The mean value of the polarization brought to the mean

height 1.08 $R_\odot$ was equal to $30 \pm 5\%$. The direction of the electric vector was nearly tangential to the limb. The continuum near the green line was underexposed, therefore we do not measure its polarization. The comparison of the spectra was made in the same way as it has been described above. In the case of 40 sec exposures, the motion of the Moon across the entrance slit of the spectrograph can give an uncertainty in comparison of three successive spectra when one identifies the points of maximum intensity in the continuum in different spectra with the same place in the corona. This uncertainty can be equal to $\pm 0.02 R_\odot$, which approximately equals one height step of the tracings. However, the account of this effect did not change (in the limits of errors) our results.

5. Discussion

Measurements of the polarization in the emission line Fe XIV 5303 Å made with two spectrographs gave similar results: at the height $\simeq 1.08 R_\odot$ (near the point of the second contact) we found a considerable polarization ($\simeq 30\%$) in the line Fe XIV; at the same time, in the red line (Fe X) the polarization was only within the range of experimental errors and did not exceed $\simeq 6\%$. The polarization in the continuum near the green and red lines on the heights (1.04–1.06) $R_\odot$ was $\simeq 35\%$. The values we obtained for the polarization in the line Fe XIV are contradictory to the results of Beckers and Wagner (1970, 1971), who measured polarization for the same eclipse all over the limb with the aid of Savart plate, but did not find polarization in the emission lines. We do not know how to explain these differences. As we have said above, the instrumental polarization effect can give errors not exceeding 10% in the extreme case of the very small polarization value. It can give some uncertainties in the polarization value in the red line. But the high polarization value in the green line cannot be attributed to this effect. It is possible that the value and the direction of the polarization in the emission lines vary from one part of the solar corona to another. In a number of theoretical papers (Hyder *et al.*, 1968; Charvin, 1965, 1971; House, 1970a, b, 1971, 1972) the authors have shown that the polarization value in the line depends on the local magnetic field in the corona and its direction relative to the observer.

Some dependence of the polarization on the local magnetic field direction may be also expected in the case of the line excitation by an electron collision. This dependence is especially important in the presence of superthermal electron fluxes generated in active regions and directed along the field. Under this circumstance the directed beam could play a significant role in the excitation of the lines. This point is also connected with the problem of the explanation of the nature of anomalously high local polarization in the continuum which had been observed during previous eclipses and was especially important during the eclipse of 7 March 1970 according to the observations by Koutchmy and Schatten (1971).

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References

Beckers, J. M. and Wagner, W. J.: 1970, *Appl. Opt.* **9**, 1933.
Beckers, J. M. and Wagner, W. J.: 1971, *Solar Phys.* **21**, 439.
Charvin, P.: 1964, *Compt. Rend. Acad. Sci.* **258**, 1155.
Charvin, P.: 1964, *Compt. Rend. Acad. Sci.* **259**, 733.
Charvin, P.: 1965. *Ann. Astrophys.* **28**, 877.
Charvin, P.: 1971, in R. Howard (ed.), 'Solar Magnetic Fields', *IAU Symp.* **43**, 580.
House, L. L.: 1970, *J. Quant. Spectrosc. Radiat. Trans.* **10**, 909.
House, L. L.: 1970, *J. Quant. Spectrosc. Radiat. Trans.* **10**, 1171.
House, L. L.: 1971, *J. Quant. Spectrosc. Radiat. Trans.* **11**, 367.
House, L. L.: 1972, *Solar Phys.* **23**, 103.
Hyder, C. L., Monter, H. A., and Shutt, R. L.: 1968, *Astrophys. J.* **154**, 1039.
Koutchmy, S. and Schatten, K. H.: 1971, *Solar Phys.* **17**, 117.
Mogilevsky, E. I., Nikolsky, G. M., and Nikolskaya, K. I.: 1960, *Astron. Zh.* **37**, 236.
Mogilevsky, E. I.: 1970, Solar Eclipse 1970 Bulletin, p. 83.