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Investigation of instrumental depolarization at the coude focus of the 1 m telescope of SAO RAS

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Abstract. Measurements of stellar magnetic fields by means of spectrophotometric observations at a coude focus are impeded by instrumental errors caused by repeated oblique reflections of light from flat mirrors. This paper deals with the investigation of instrumental depolarization at the coude focus of the 1 m telescope of SAO RAS. Account of this effect will improve the accuracy of measurements of magnetic fields.

Key words: astronomical instrumentation: telescopes – astronomical techniques: polarimetry

1. Introduction

One of the main techniques of measurement of stellar magnetic fields is based on obtaining Zeeman spectra, that is, obtaining of a spectrum in two reciprocal circular polarizations with a high spectral resolution (no less than 25000). Spectra are mostly taken with spectrometers placed at the coude focus. Unfortunately, coude foci have one essential shortcoming: when a beam of light is reflected from diagonal coude mirrors before entering the spectrometer, instrumental polarization and depolarization arise, which degrades the accuracy of spectropolarimetric study. This problem has been extensively discussed by Babcock (1958), Wolff & Bonsack (1972), Borra (1976), Borra and Vaughan (1977), Nariai (1982), Capitani et al. (1989), Bychkov et al. (1999), and other authors. We estimate herein instrumental circular depolarization from direct measurements. Account of this effect will improve the accuracy of magnetic field measurements when processing Zeeman spectra.

2. Observations

The polarimeter MINIPOL (Dolan & Tapia, 1986) seems to be the most useful device to study circular instrumental depolarization, for it makes possible investigation of polarization in a wide spectral range, from 3000 to 9000 ÅÅ (Johnson UBVRI filters). The polarimeter MINIPOL is designed to study linear polarization, but there exists a standard procedure that enables measuring circular polarization also. For this purpose, a linear achromatic phase-shifting plate introducing a phase shift of 90° ($\lambda/4$) was placed at the polarimeter entrance. This plate is oriented so that azimuth of its optical axis is perpendicular to the azimuth of the fast axis l of the polarimeter, i.e. increasing thus the phase along the axis r. With this orientation of the plate, the phase shift produced by it will be described, according to Schurcliff (1962), by Mueller matrix

$$F = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{pmatrix}. \tag{1}$$

If the incoming beam of light is described by the Stokes vector $S = (I, Q, U, V)$, the light that has passed the installed phase plate will have the parameters:

$$S' = F \times S = (I, Q, V, -U). \tag{2}$$

That is, while measuring the parameters Q and U the polarimeter MINIPOL will measure V instead of U in the case the plate is installed. The polarimeter MINIPOL thus fitted measures sequentially all 4 Stokes parameters. The best way to examine the degree of instrumental circular depolarization is to bring to the entrance circulary polarized light. Then having measured the polarization at the output, one can judge how strong the depolarization is. For this study to be carried out with a maximum correctness, a polarization calibration unit was constructed that would convert the incoming unpolarized light to completely circularly polarized without deflection of the incident light beam. The polarization calibration device meeting these requirements was made as follows. First, a linear polaroid $\lambda/2$ is installed, which is described by Mueller matrix

$$F1 = \begin{pmatrix} 1/2 & 1/2 & 0 & 0 \\ 1/2 & 1/2 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}. \tag{3}$$

Table 1: *The parameters of the phase-shifting plates employed in the polarimeter MINIPOL and in the calibration unit*

	Phase shift in degr.	
λ (Å)	MINIPOL	Calibration
3800	81.4	80.3
4000	87.1	86.3
4500	90.0	90.6
5000	90.7	91.4
5500	91.0	91.5
6000	91.3	91.3
6500	91.5	91.5
7000	91.4	91.4
7500	90.6	90.6
8000	88.7	88.9

Then a linear phase-shifting plate of 90° ($\lambda/4$), whose fast axis makes with the linear polaroid fast axis an angle of 45°, was mounted. This phase plate is described by Mueller matrix

$$F2 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}. \qquad (4)$$

If the input unpolarized light beam is described by the Stokes vector $S = (I, Q, U, V)$=(1,0,0,0), then the light beam that has passed through this polarization device will have the parameters

$$S' = F2 \times F1 \times S = (1/2, 0, 0, 1/2). \qquad (5)$$

That is, this device transforms unpolarized light into 100 % circularly polarized. Naturally, this is how the ideal device should operate in the ideal case. The parameters of the real device are computed proceeding from the parameters of real elements incorporated in it. In Table 1 are collected the parameters of the phase-shifting plates employed in the polarimeter MINIPOL and in the calibration unit. In the first column is indicated the wavelength, the next two columns give the phase shift in degrees, respectively.

The mean parameters of the linear polaroid in the Johnson UBVRI filters were derived with the polarimeter MINIPOL. To do this, the polaroid was placed in front of the polarimeter entrance. The zero polarization standards HD 21447 and HD 21231 from the list of Turnshek et al. (1990) were used as sources of unpolarized light. The transmission values of the light filters vrs wavelengths are presented in Fig. 1.

Table 2 gives the effective filter wavelengths, the value of the positional angle at the corresponding wavelength of the polaroid in degrees, and the depth of modulation in per sent. The depth of modulation characterizes the integral value of conversion of the emission phase state and is expressed by

$$m = 100\% \cdot (I_{max} - I_{min})/(I_{max} + I_{min}), \qquad (6)$$

where I_{max} and I_{min} are the intensities after passing through the phase element.

Table 2: *The mean parameters of the linear polaroid in the Johnson UBVRI filters*

Filter	Center λ(Å)	Positional angle	Depth of modulation %
U	3550	177.8	73.5
B	4650	178.3	84.1
V	5500	180.0	89.7
R	6900	180.1	95.8
I	8000	180.1	53.8

Table 3: *The estimates of the expected polarization (V Stokes parameter) for each filter*

Filter	V %
U	63.1
B	82.4
V	87.9
R	83.7
I	52.6

Fig.2 shows the optical layout with the location of the polarimeter, where 1 is the main mirror, 2 is the secondary mirror, 03 is the first diagonal mirror, 04 is the second diagonal mirror, 05 is the third diagonal mirror, Pol is the polarimeter MINIPOL, Calibr is the place where the calibration unit is mounted.

The main and secondary mirrors of the telescope do not give essential phase shifts into the object emission, because they are perpendicular to the light beam axis. Instrumental effects (depolarization, polarization) are produced by the inclined (by 45°) flat mirrors 03 and 04 which reflect and divert the beam through 90°. When studying instrumental depolarization a coordinate system was chosen that bounds the object on the celestial sphere with orientation of the inclined mirrors — the same as in the paper by Bychkov et al. (1999). To obtain estimates of the expected polarization, the following procedure was applied. Variations of the phase shift vrs wavelengths for each phase-shifting plate were approximated with smooth curves. These curves were used to find the value of the phase shift for effective wavelengths of the light filters. Then a standard procedure of mathematical convolution of these curves with the curves

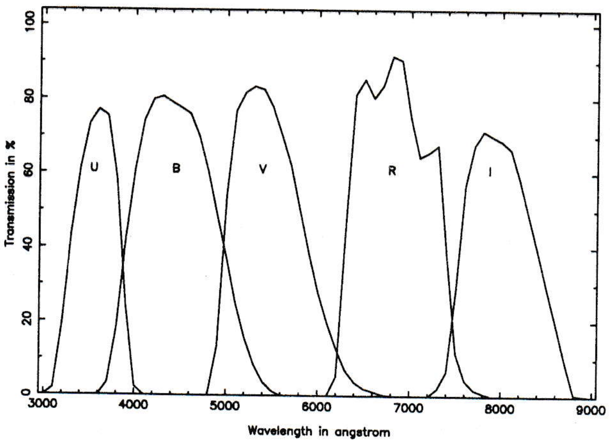

Figure 1: *Curves of transmission of the UBVRI filters incorporated in the polarimeter MINIPOL.*

Table 4: *Zero polarization stars used in measurements*

Name	m_v	α	δ	*Sp*
αLyr	0.03	18 36 56	+38 47 01	*A0V*
αPeg	2.49	23 04 46	+15 12 19	*B9V*
γCas	2.47	00 56 43	+60 43 00	*B0IV*

of transmission of the filters was applied. The estimates of the expected polarization (V Stokes parameter) thus obtained are listed in Table 3.

In order to make the measurements approach real observations with their ray diagram as closely as possible, it was decided to use the light of bright stars in the measurements.

The calibration unit had a throughput of 20 % and a light diameter of 30 mm. For this reason, it was placed inside the telescope tube just in front of the inclined diagonal mirror 03, which is equivalent to the entrance pupil of about 240 mm in diameter. This approach is warranted since the main and secondary mirrors do not introduce significant instrumental effects. The facility was used in the observations on the night of August 13/14, 1998. Three stars with unpolarized light were selected for the observation. The stars were chosen so that they are located at different inclinations (see Table 4).

A theoretical curve of the expected value of polarization with variation of an hour angle t was computed for each star. As the initial values of the Stokes parameter, the data of Table 3 were used in the calculation. Variation of circular polarization with an hour angle for the star γ Cas is displayed in Fig.3 for the U filter. Similar relationships in the B and V filters obtained for γ Cas are given in Figs.4 and 5, for α Peg in the R filter in Fig.6, and for the star α Lyr in the I filter in Fig.7.

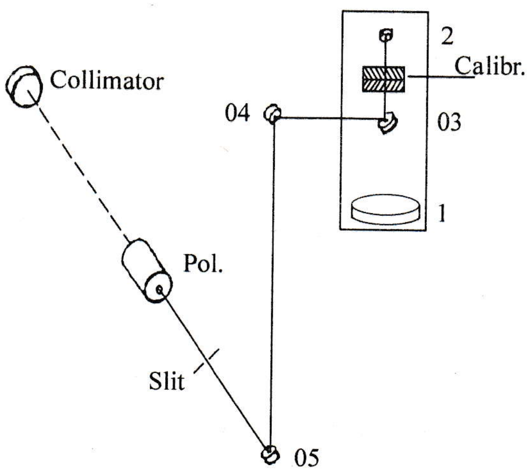

Figure 2: *The location of calibration device and polarimeter in optical layout of the telescope.*

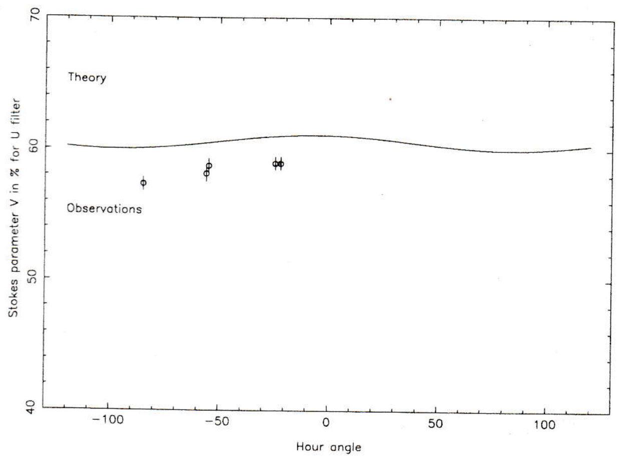

Figure 3: *Measured (estimates with bars) and calculated (curve) polarization for different values of the hour angle in the U filter.*

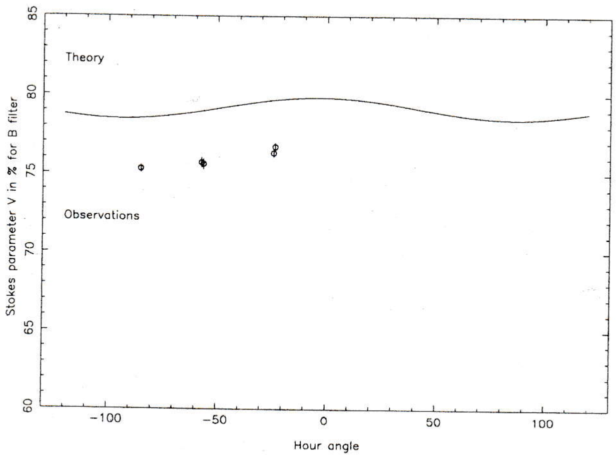

Figure 4: *The same as in Fig. 3, but in B filter.*

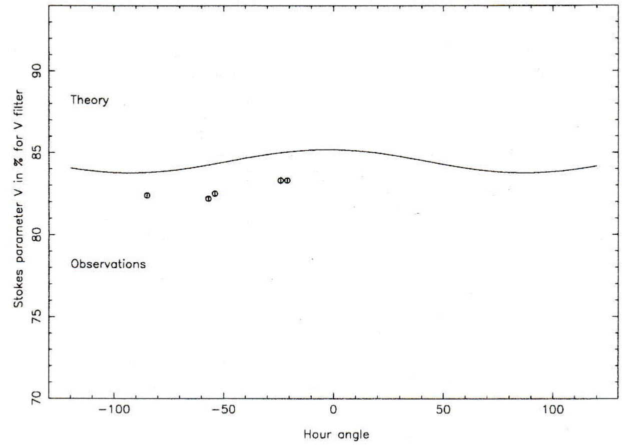

Figure 5: *The same as in Fig. 3, but in V filter.*

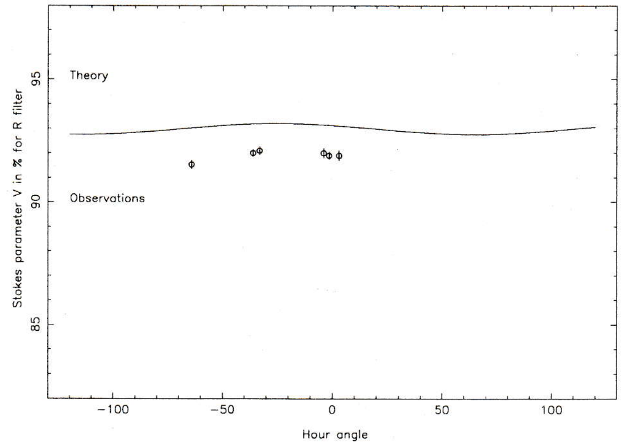

Figure 6: *The same as in Fig. 3 for α Peg in R filter.*

3. Discussion of results

Using all estimates made from these three stars, the mean ratio of the measured circular polarization, V_{obs}, to the calculated, V_{calc}, was found. This ratio represents the part of circular polarization that remained after reflection of the light beam from the inclined diagonal mirrors:

$$k = 100\% * V_{obs.}/V_{calc.} \qquad (7)$$

This is the best expression which helps to derive depolarization in relative units, because the light detector (usually a CCD) keeps record of the intensity of radiation, but not the phase shift between the Fresnel amplitude coefficients r_s and r_p of the electric vector. The depolarization value is calculated by the formula:

$$Dep = 100\% * (V_{calc.} - V_{obs.})/V_{calc.} \qquad (8)$$

The data obtained are given in Table 5 and Fig.8.

The data show that the depolarization does not exceed 5% within the wavelength range 4500–8500 ÅÅ and increases to 10% and more in the U

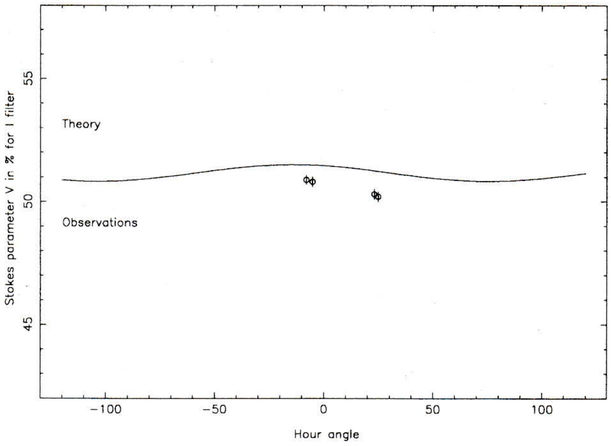

Figure 7: *The same as in Fig. 3 for α Lyr in I filter.*

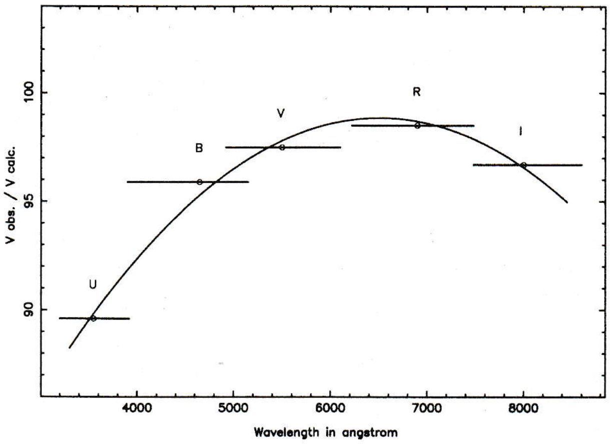

Figure 8: *Circular polarization as a function of wavelength.*

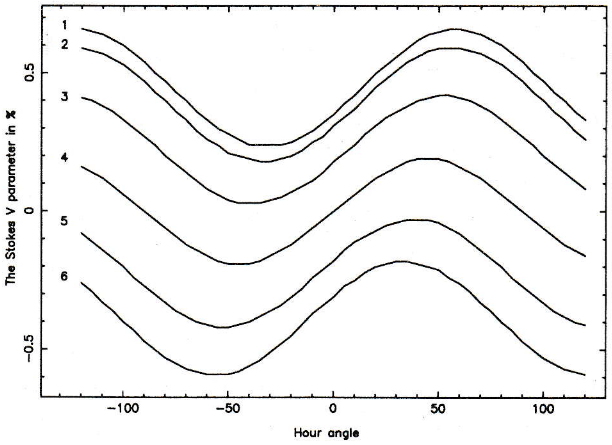

Figure 9: *Instrumental polarization as a function of t, calculated for different declinations δ: 1 — 45°; 2 — 30°, 60°; 3 — 15°, 75°; 4 — 0°, 90°; 5 — −15°; 6 — −30°.*

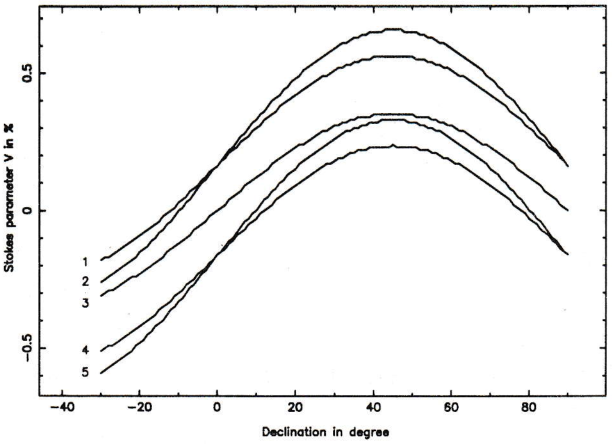

Figure 10: *Instrumental polarization as a function of δ calculated for different hour angles t: 1 — 30°; 2 — 60°; 3 — 0°; 4 — −30°; 5 — −60°.*

Table 5: *Coefficients k and depolarization values for each filter*

Filter	Center λ(Å)	k %	*Dep* %
U	3550	89.6	10.4
B	4650	95.9	4.1
V	5500	97.5	2.5
R	6900	98.5	1.5
I	8000	96.7	3.3

filter. There are all the grounds to believe the observed instrumental effects change smoothly with wavelength. For the sake of convenience of taking them into account, an analytical expression describing the behaviour of k with wavelength λ has been found:

$$k = 55.1983 + 0.134146 \times \lambda - 1.03047 \times 10^{-6} \times \lambda^2. \quad (9)$$

Depolarization values are on average a few per cent and do not go over 10% (Table 5). Proceeding from this, it is relatively easy to calculate the value of the instrumental circular polarization caused by reflections of the light beam from the diagonal mirrors and then simulate its behaviour depending on declination and hour angle. The results of the calculations are presented in Figs. 9 and 10. The calculations were made for the case where the incoming beam of light is not polarized, that is, represented by the Stokes vector $S(1,0,0,0)$.

4. Conclusions

As a result of the work done, we have managed the followings.

1. To ascertain that the value of instrumental circular depolarization does not on the average exceed a few per cent and reaches 10% in the violet spectral region. An analytical expression describing the behaviour of depolarization with wavelength has been found.
2. To estimate the value of instrumental circular polarization and its behaviour with hour angle t and declination δ.

The data obtained make it possible to take correct account of instrumental effects arising in magnetic field measurements made at the coude focus of the 1 m telescope of SAO RAS, which will eventually improve the accuracy of observational data.

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