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A spectropolarimeter based on the 6 m telescope fast prime focus spectrograph

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Abstract. A description is presented of a spectropolarimeter designed on the basis of fast prime focus spectrograph of the 6 m telescope for measurements of the four Stokes parameters. The optical layout, design of the polarization measuring device and performance characteristics of the spectrograph oriented as a spectropolarimeter are given. The circuit of automatic control of the apparatus and the techniques of polarimetric observations are described. Results of measurement of circular and linear polarizations of standard stars are shown.

Key words: telescopes: 6 m telescope — instrumentation: spectropolarimeter

1. Introduction

The low level instrumental polarization and the minimum losses of light in observations at the BTA prime focus make it attractive for investigation of polarization and magnetic field measurements in faint stars and other objects. In the early 1980s, a hydrogen-line magnetometer (Shtol' et al., 1985) was developed for the prime focus of the 6 m telescope. A photomultiplier used as the detector measured either in a narrow wavelength interval (e.g. in the wings of hydrogen lines) or in medium spectral bands ($\Delta\lambda \approx 600\,\text{Å}$). This circumstance caused necessity for designing a new polarimeter operating in the spectral mode of simultaneous measurement of polarization in a wide wavelength range.

We made a decision to equip the already existing fast spectrograph UAGS of the 6 m telescope prime focus (Afanasiev et al., 1995) with a polarimetric device measuring the 4 Stokes parameters. Observations with this device are made at the moment with the use of a CCD camera "Photometrics" of 1024×1024 ($24 \times 24\mu$m) and a standard F:1.5 external focus camera UAGS. To reduce the time of reading the spectra from the CCD, a region of 1024×330 pixels is generally recorded. The slit length actually used is 270 pixels, or 110 seconds of arc. A set of diffraction gratings (325, 651 and 1302 g/mm) enable obtaining spectra with reciprocal linear dispersions of 4.6, 2.3 and 1.2 Å/px with a spectral resolution of ≈ 3 px with a slit width of 2 seconds of arc. The basic units of the spectrograph are remotely controlled from the BTA control room. The electronics and software are currently upgraded to provide full automation of the observing process. A relatively good throughput of the spectrograph in conjunction with high quantum efficiency of the CCD and remote control make it convenient for spectropolarimetric observations.

When developing the polarization analyser, we proceeded from three obvious requirements to its design. First, as the apparatus is intended for investigation of faint objects, the new polarimetric analyser must have minimum light losses in measurement of all the Stokes parameters. Second, the classical requirement is the utmost removal of instrumental effects. The third requirement which follows from the necessity for intelligent use of the observational time is full automation of the instrument.

2. Design features, technical characteristics of the polarization analyser and the optical arrangement of the polarimeter

Polarization studies generally require long times of signal acquisition because the degree of polarization is low as a rule. For this reason, when designing polarization devices, all possible instrumental effects and the distortions introduced by the polarization optics should be taken into account to the utmost.

The first distorting factor is that the polarization analyser is a plane-parallel plate, which, as it is known, causes positive spherical aberration (Maksutov, 1946). This factor is, however, partially made up for by the main mirror of the telescope. Spherical mirrors are known to have negative spherical aberration, which has a crucial effect on the resulting images at large angles of beam convergence. The beam convergence of the 6 m telescope is defined by its relative aperture, which is 1:4. This makes it possible to use rather thick crystals, which partially compensate for positive (analyser) and negative (main mirror) aberrations.

The second distorting factor is that the image of the star in one polarization has an elliptical shape at an exit of the Iceland spar crystal (Kruger et al., 1967). Such a geometry of the star images does not ensure passage of equal fluxes from these images through the spectrograph slit.

The third significant distorting factor is the dispersion of the deflected beam in the Iceland spar crystal. The dispersion enlarges the size of a single beam. The orientation of polarization of two beams with respect to the slit plays an important part when operating the polarization analyser with the spectrograph. If the orientation of one of the orthogonal polarizations of the source does not coincide with that of the slit, this causes its weakening by the diffraction grating. The images may rotate not-symmetrically about the analyser axis. That is why, the two beams are not symmetric about the optical axis of the spectrograph. The factors indicated affect somehow the measurement accuracy.

To remove the enumerated shortcomings, the analyser was built using the following technology. The Iceland spar crystal was sawn in parallel to its natural sides into two equal parts. These two parts turned by 90° with respect to each other were then cemented together. This structure has the following advantages over the classical scheme (Babcock, 1947).

- The optical paths of the two rays in the calcite block are equal.
- When turning the calcite block round the optical axis of the analyser, the images rotate symmetrically about it.
- The two rays have the same dispersion in wavelengths.
- The ellipses of the images make an angle of 45° with respect to the spectrograph slit.

Below we present the specifications of the polarimetric device designed for the fast spectrograph of the 6 m telescope prime focus.

- Operating range is 3400–12000 Å.
- Separation of the images at the calcite block exit is 1mm.
- Axes ratio of the ellipse of the star images at the calcite block exit is 4:5.
- Calcite block thickness is 14 mm.
- Calcite block diameter is 30 mm.
- Transparency of the analyser under the condition of linear polarization measurement is 0.9.
- Transparency of the analyser under the condition of circular polarization measurement is 0.8.

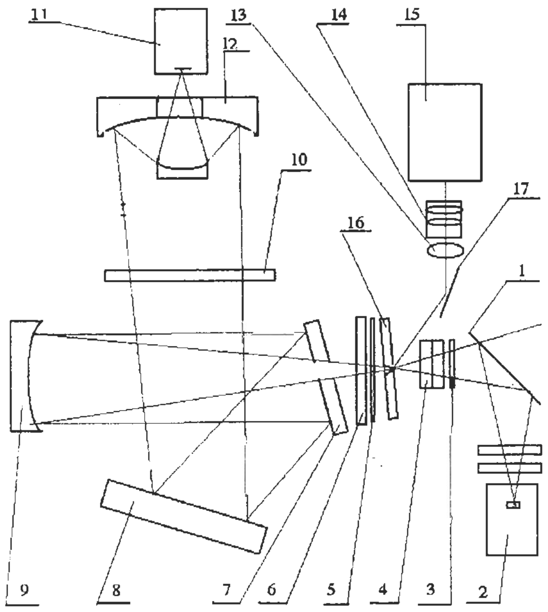

Figure 1: *The optical arrangement of the spectropolarimeter.*

2.1. Design of the analyser

The polarization analyser (the above-described calcite block + a phase-shifting plate "$\lambda/4$") is located in front of the spectrograph slit. The mechanical part is assembled on one stepping motor and has four positions:

1. The polarization analyser is off the beam;
2. The calcite block is in the working beam;
3. The calcite block and the phase plate (with orientation of the fast axis at +45°) are in the beam;
4. The calcite block and the phase plate (with orientation of the fast axis at −45°) are in the beam.

Owing to the design features of BTA, in particular, to the availability of the telescope field rotation compensator (P2), linear polarization can be measured without additional phase devices. Such measurements are made when the analyser is in the beam. Its turn is specified with the aid of the P2.

2.2. The optical layout of the spectropolarimeter (analyser+UAGS)

The optical layout of the spectropolarimeter is shown in Fig. 1. It incorporates:

- comparison spectrum diverting mirror (1);
- comparison spectrum lamp (2);
- entrance phase plate $\lambda/4$ (3);
- composite calcite block $CaCO_3$ (4);
- shutter (5);
- order-separating filter (6);
- flat diagonal mirror (7);
- diffraction grating (8);
- collimator mirror (9);
- Schmidt plate (10);
- CCD detector (11);
- mirror of the external focus camera (12);
- focusing lens (13);
- objective lens for viewing the field (14);
- TV guide (15);
- spectrograph slit (16);
- flat diagonal mirror for slit viewing (17).

When measuring the Stokes parameters I, Q and U, the phase plate (3) is withdrawn from the beam. The measurements are made at two angles, 0° and 45°, which are fixed by slewing the telescope field rotation compensator.

When circular polarization is measured the phase plate is used. It is located so that the fast axis makes an angle of +45° with respect to the calcite block axis. The composite calcite block $CaCO_3$ has the axes of maximum transmission 45° and −45°, which are oriented along the spectrograph slit.

2.3. Automation and control electronics of the spectropolarimeter. Specifications of the spectropolarimeter

Control of the power units of the spectropolarimeter is implemented by a computer (via the standard port of input/output) and a unified control unit (UCU). Control of the position of the mechanisms is realised via electromechanical transducers and stepping motors. The software and hardware enable use of different light detectors.

Power supply units and electronic switches of the actuating electromechanical devices are withdrawn from the working space to diminish heat evolution inside the spectrograph. Commutator and stepping motors are used as power elements. The logic spectrograph control, execution of commands of the control computer, count of the steps of the motors, reception of signals of the transducers of positions of the mechanisms and their transmission to the computer are executed by the UCU. The UCU is made on chips of the programmed logic (PLD); the power switches of the actuating devices are built on superminiature MOSFET transistors of the firm IR. The control devices are designed so that they have minimum power consumption and maximum electronic anticountermeasures because the light detectors used have low noise characteristics. The UCU is built in a separate screened housing and located on the exterior surface of the spectrograph.

2.4. Specifications of the spectropolarimeter

1. Light transmission in one polarized beam under the condition of measurement of the Stokes parameters:

parameter U — 0.90,
parameter Q — 0.90,
parameter V – 0.80.

2. Working spectral range is 4000–7100 Å.
3. Linear dispersion is 1–7.5 Å/px.
4. Time of installation of the analyser is 60 s.

3. Procedure of polarization measurements

Because of the alt-azimuth mounting of the 6 m telescope, polarization measurement should be made with the system P2 on. For this reason, not all the calculation of the polarization plane angle is convenient to make with respect to the initial spectrograph slit position. The final result can be obtained with allowance made for the position angle of slit orientation in P2. Hereafter the position angle of the slit in the P2 system will be called "slit angle", and, for the sake of simplicity in presentation, its initial position is assumed to zero.

For the computation of the Stokes parameters and elimination of instrumental polarization, images of polarized spectra from the object being investigated are obtained in six positions of the spectropolarimeter.

- **Measurement of the parameter U**

The first exposure is made at a slit position angle of 0°. The second exposure is made with the P2 turned by 90°.

- **Measurement of the parameter Q**

The third and fourth exposures are fulfilled with a 45° and −45° turn of P2, respectively.

- **Measurement of the parameter V**

Measurement of the parameter is made with the phase plate $\lambda/4$ inserted (the fast axis is oriented at +45°). The next exposure is accomplished with $\lambda/4$

swang by 90° from the initial position (corresponds to the fast axis orientation of −45°).

Hereafter, we will call these 6 successive exposures "basic frames" or simply "frames" numbered in order of acquisition.

The recommended reduction of data is based on the standard software used in SAO and consists in the following. The primary reduction with initial images is performed in the standard manner in the MIDAS environment (Knyazev & Shergin, 1994). After that the parameters U$_1$ and U$_2$ are computed from the extracted polarized spectra corresponding to the 0° and 90° positions of the apparatus:

$$U_1 = \frac{I_{1L} - I_{1R}}{I_{1L} + I_{1R}},$$

$$U_2 = \frac{I_{3L} - J_{3R}}{J_{3L} + J_{3R}},$$

where I_{1R} is the spectrum intensity in an ordinary ray (R) of the analyser of the first frame, I_{1L} is the spectrum intensity in an inordinary ray (L) of the analyser of the first frame, J_{3R} and J_{3L} are the same for the third frame.

The parameter U is calculated through averaging of the derived values of U_1 and U_2.

The parameter Q is computed in a similar manner, also from two frames corresponding to the position of the device at 45° and −45°:

$$Q_1 = \frac{I_{2L} - I_{2R}}{I_{2L} + I_{2R}},$$

$$Q_2 = \frac{I_{4L} - I_{4R}}{I_{4L} + I_{4R}},$$

and then $Q = (Q_1 - Q_2)/2$, where I_{2R}, I_{2L} are the intensities of the second frame,
I_{4R}, I_{4L} are the intensities of the fourth frame.

The values and the angles of polarization are calculated in the standard way:

$$P = \sqrt{U^2 + Q^2},$$

$$\Psi = arctan\frac{U}{Q}.$$

The parameter V is computed by measuring V_1 and V_2:

$$V_1 = \frac{I_{5L} - I_{5R}}{I_{5L} + I_{5R}},$$

$$V_2 = \frac{I_{6L} - I_{6R}}{I_{6L} + I_{6R}},$$

where the intensities are also numbered in order of numbering the frames.

Finally $V = (V_1 - V_2)/2$.

The described procedure of computing the Stokes parameters eliminates to the utmost all instrumental errors.

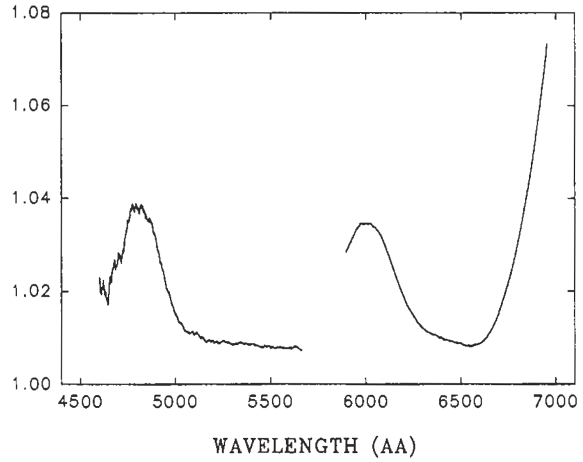

Figure 2: *The modulation depth coefficient K vrs wavelength.*

4. Experimental test of the method

4.1. Laboratory test

Here we present two main tests for investigation of the performance of the device. The tests were made under the laboratory conditions. Polarized light from the "artificial star" was recorded. From the results of the first test we present the value of the coefficient of the depth of modulation K of the device (in the system spectrograph + polarization analyser) in different wavelength ranges. The modulation depth coefficient is dimensionless value (≥ 1) by which the result of polarization measurement and its error should be multiplied to make the result a "true one". Knowledge of this coefficient is necessary because any "real" polarimeter introduces its intrinsic depolarization as a result of imperfection of its polarization optics, minor inaccuracies of adjustment and internal reflections in the spectrograph. The results of the test are given in Fig. 2.

As one can see from the figure, the coefficient of modulation depth is $k \approx 1.0$ practically in all the working wavelength range. It can be said for comparison that the coefficient of modulation depth of the hydrogen-line magnetometer (Shtol' et al., 1985) has a mean value of about 1.1 in the deep part of the spectrum. Thus, the average depolarization in the polarimeter is less than 2 % (K< 1.02) for the wavelength range 4500 to 6750 Å.

Use of the coefficient K measured under laboratory conditions for reduction of real observations is not quite correct in terms of methodology because this coefficient may vary with time depending on temperature and observing conditions. However, these variations are small and can change the depolarization coefficient itself by no more than a few per cent. As practice has shown, correct account of depolarization in polarization measurements can be made by

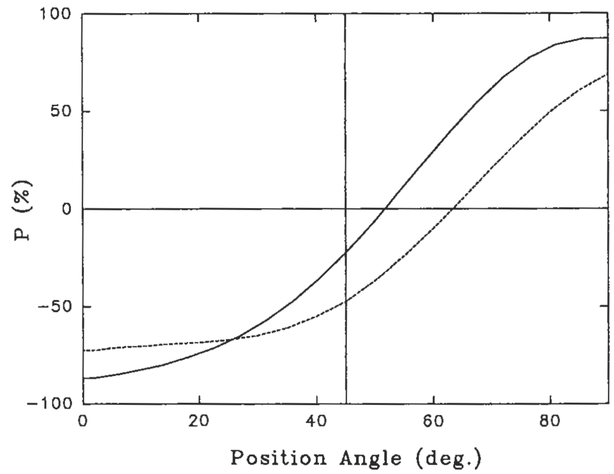

Figure 3: *Recorded circular polarization of the laboratory source against position angle of the phase plate* $\lambda/4$. *The solid line represents the measurements in the region 4900 Å, the dashed line shows those in the region 6800 Å.*

observing spectrophotometric polarization standards. Since the depolarization of the device that we have measured is no more than 5–8 per cent throughout the working wavelength range, we ignore the labour-consuming calibration measurements of the dependence of K on the environment and believe that all minor uncertainties introduced by depolarization can be allowed for in observations of polarization standards. In the future, we shall carry out a more detailed inspection of the polarization optics stability.

The second test is connected with examination of the known symmetry in measurements of circular polarization in the positions of the phase plate $\lambda/4$ which correspond to the orientation of its axis +45° and −45°.

As it follows from the methodological recomendations given above, in an ideal case of observations of circular polarization not varying with time, V_1 and V_2 must give values equal in module, but opposite in sign. This circumstance is very important in observing the Zeeman effect in spectral lines of stars and defines the methodological solution of such observations: when observing circular polarization of opposite signs in the wings of spectral lines in the two positions of the phase plate $\lambda/4$, one can significantly improve the accuracy of circular polarization measurements in lines and take account of practically all systematic effects.

Thus, in the second test, which is illustrated in Fig. 3, we measured circular polarization from the laboratory light source in all possible positions of the phase plate $\lambda/4$ (from −45° to +45° in the polarimeter system or from 0° to 90° in the system of the polarization analyser). As can be seen from Fig. 3, the extreme (operating) positions of the phase plate give a symmetric result with high accuracy. The intermediate positions are not as symmetric about the 45° position (zero position in the polarization system). These intermediate positions are not operating, they are presented to illustrate the presence of internal stray polarization of the spectropolarimeter. The given instrumental systematic errors are completely eliminated by averaging the two chosen modules of measured polarization symmetric with respect to the zero position.

Note in conclusion that the extreme values of the measured circular polarization for the blue and red parts of the spectrum do not reach 100 %. This is only due to the fact that the laboratory circular polarization light source does not give strictly circular polarization in the whole visible range. Thus, the given test should not be treated as one for depolarization. Our additional measurements of the K coefficient with the phase plate inserted have yielded virtually the same results as in Fig. 2. All the above recomendations concerning linear polarization observations can be repeated for circular polarization measurements as well.

4.2. Test measurements of standard stars

The standard stars GRW +70°8247 and HD 215441 were observed.

Fig. 4 shows Zeeman spectra in the rays R and L of circular polarization of the magnetic white dwarf GRW +70°8247 with the phase plate fast axis orientation at 45°. Figs. 5, 6, 7 demonstrate the parameters V, U and Q for the same star. The results of the computations of P and polarization angle Ψ in the spectrum of GRW +70°8247 are presented in Figs. 8 and 9, respectively. Analysis of experimental data obtained from this well-known standard star shows good agreement with measurement results of other authors (see, for instance, Landstreet & Angel, 1975).

It should be noted that in acquisition and analysis of data, standard stars of "zero" linear and circular polarization were not used, which suggests good performance of the device itself and the applied techniques of observation. The observations were conducted on a moonless night under good weather conditions. An additional investigation has shown, however, that to achieve polarization measurement accuracy from the spectra (not in lines) better than 0.25 %, observations of both zero and non-zero standards of polarization are desired. Observations of polarization standards on moonless nights are obligatory.

All above said was related to polarimetric investigations of circular and linear polarizations of stars having polarization in the continuum. Results of test measurements of magnetic Ap/Bp stars, which reveal

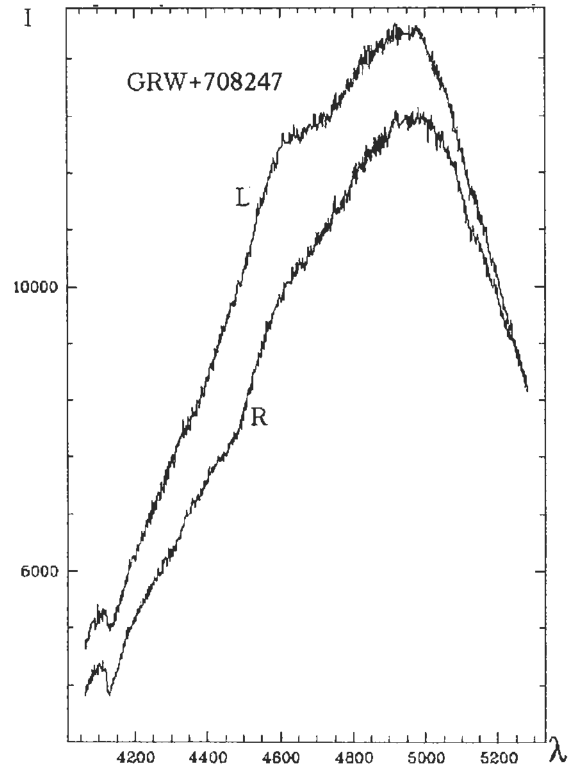

Figure 4: *The spectra in the rays R and L of circular polarization of the white dwarf GRW* +70°8247 *with the orientation of the fast axis of the plate* λ/4 *at* 45°.

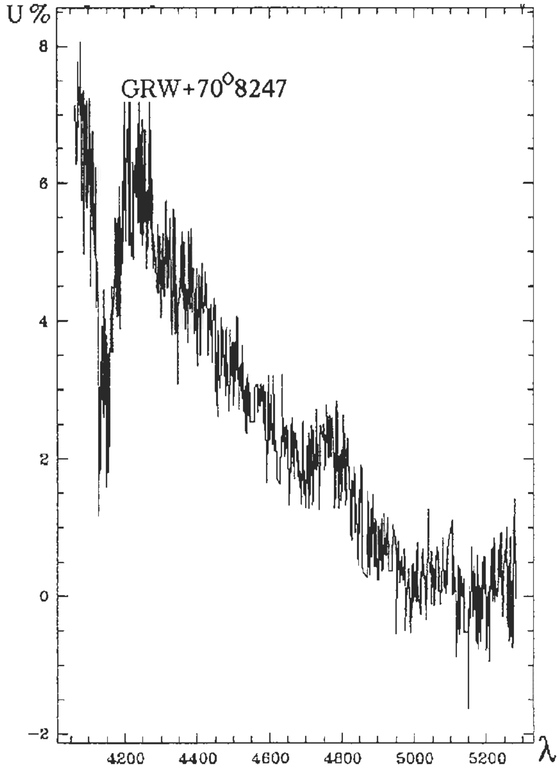

Figure 6: *U-parameter spectrum of GRW* 70°8247.

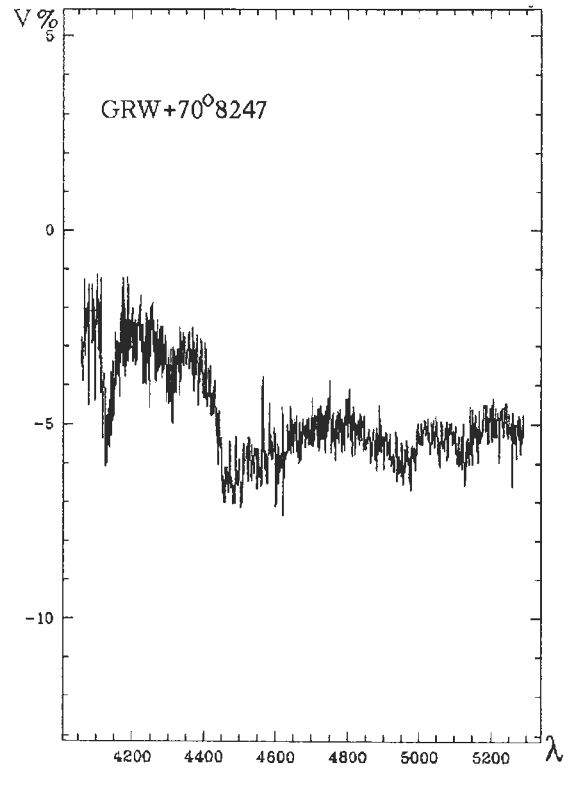

Figure 5: *V-parameter spectrum of GRW* 70°8247.

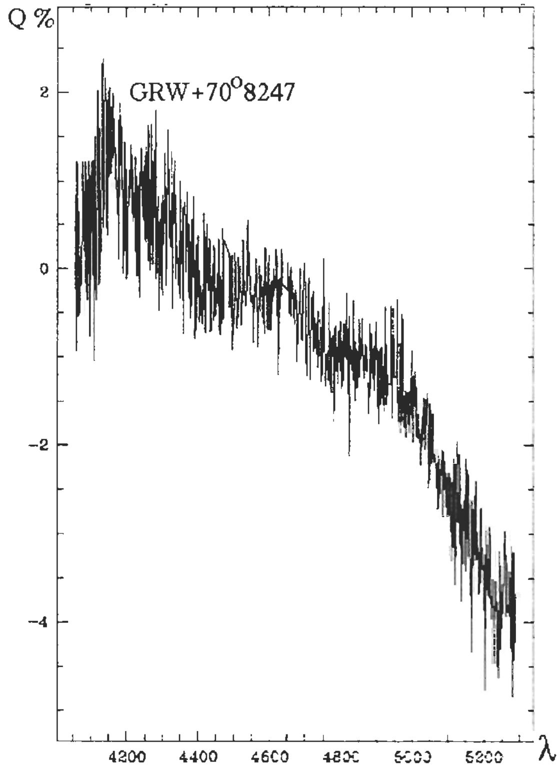

Figure 7: *Q-parameter spectrum of GRW* 70°8247.

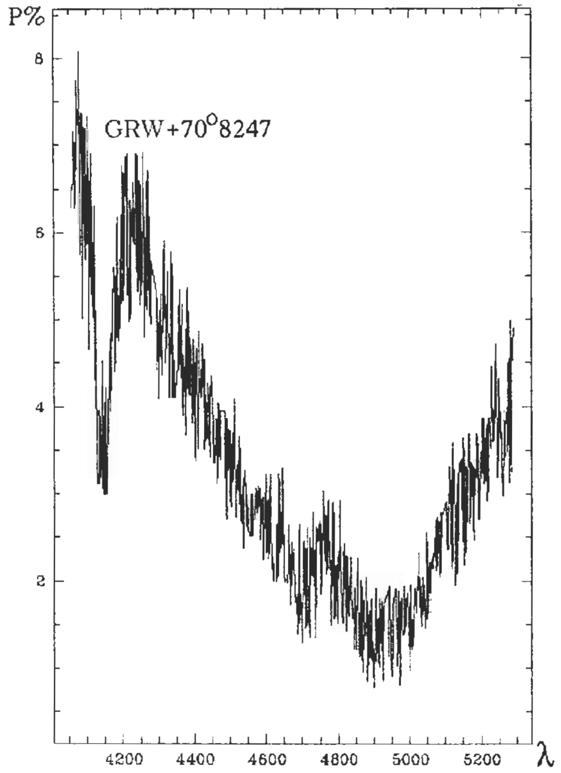

Figure 8: *Linear polarization P over the spectrum of GRW* 70°8247.

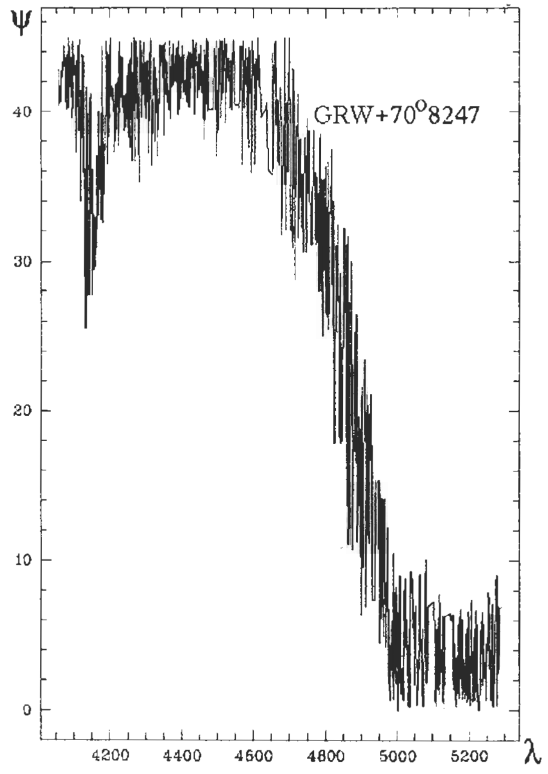

Figure 9: *Orientation of linear polarization* Ψ *in GRW* 70°8247.

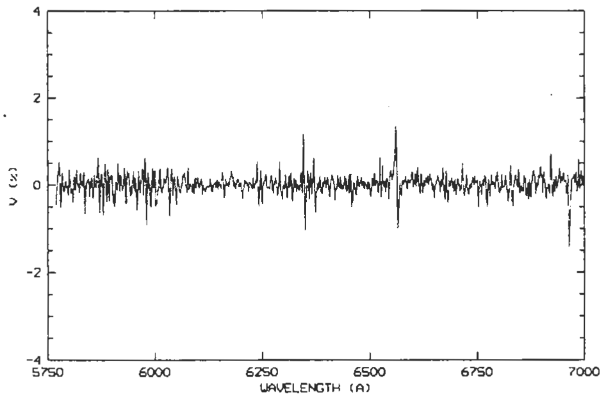

Figure 10: *Circular polarization V in the spectrum of Babcock star: the maximum value (1.3 %) in the H_α line corresponds to the effective magnetic field* B_e = 7300 *G.*

polarization only in the central regions of their spectral lines show that the polarimeter can be used efficiently in Zeeman observations of faint stars with magnetic fields over 300–400 G. Fig. 10 displays a result of observation of circular polarization in the spectrum of the magnetic star HD 215441 (Babcock star). The circular polarization in spectral lines at the given wavelengths reaches its maximum (1.3 %) in the region of the H_α line and corresponds to the magnitude of the effective magnetic field, $B_e = 7300$ kG.

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