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Polarimetry and spectropolarimetry of stars. Devices and methods

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A brief description is given of selected spectropolarimeters designed for telescopes of different diameters to study star light polarization. A program of development of stellar spectropolarimetry technique for the telescopes of SAO RAS is formulated.

Key words: methods: observational – techniques: polarimetric

1. Introduction

Polarization of radiation of cosmic sources provides information about physical characteristics of sources: strength and geometry of magnetic fields, chemical composition, shape, dimensions, concentration and orientation of particles scattering the radiation, about the degree of homogeneity of the surface brightness of an astronomical object. The polarization may arise either in the source itself or (and) in the medium between sources and the observer. In the case of point sources polarization of radiation may prove to be the only channel bearing information on the inner (spatially unresolved) structure of the object. Investigation of polarization is the most important test for the determination of the mechanism of generation of radiation under the cosmic conditions: scattering on small particles (from specks of dust to electrons), synchrotron radiation of relativistic electrons in magnetic fields.

Magnetic fields control the motion of matter in the Galaxy. The strengths of cosmic magnetic fields varies within a wide range: from 10^{-6} G in the interstellar medium to 10^{12} G and more in magnetospheres of pulsars. Magnetic fields with an intensity of 10^{-9} G in the intergalactic medium have an effect on the behavior of matter near galaxies not less than fields of neutron stars (10^{12} G) affect the motion of the surrounding plasma.

When measuring circular and linear polarization, various manifestations can be revealed of magnetic fields present in the medium where basic properties of the radiation form (i.e. in the stellar atmosphere and circumstellar envelope). Proceeding from the above said, the instrumentation intended for the investigation of polarization of astrophysical objects must have a wide range of sensitivity and spectral resolution.

At the telescopes of SAO a certain place is taken by polarimetric and spectropolarimetric observations. As the generations of light detectors change, the procedure of analysis of polarization properties of radiation also improves. The development of efficient spectrographs provides for new modes of spectropolarimetric observations. The aim of this review is elucidation of the fundamental tendencies in the development of instruments and methods for spectropolarimetry of stars and judgement of prospects of using them in SAO. Of course, we do not pretend to the completeness of mentioning all realized methods and to the exhaustive numbering of possible ways of development. Before turning to the description of different spectropolarimetric systems, some fundamental principles of spectropolarimetry will be recalled.

2. Devices and methods for the analysis of polarized radiation

The simplest device for the analysis of polarized radiation is a film or a crystal polaroid. In astronomical practice such analyzers are used only for calibration. In photographic recording two-beam analyzers, which record ordinary and extraordinary rays simultaneously were practiced on a large scale. The use of the simplest two-beam analyzers leads both to defocusing of one of the images and to different intensities, which is due to the difference in transmission of the ordinary and extraordinary rays by the optical elements of the spectral device. The simplest way to solve this problem is the use of two equal calcite plates whose axes are at a right angle to one another. The two-beam analyzers diverging the beams to a large angle (Glan-Foucault prism and its modifications, Glan-Thompson prism, a cube with a thin-film diagonal plane, etc.) were basically used in polarimeters with photomultipliers. Other types of analyzers — Rochon, Senarmont, Wollaston prisms — were also used in similar layouts.

When analyzing circular polarization, devices are used, which convert circularly polarized radiation into linearly polarized radiation. For this purpose, plates shifting the phase by $\pi/2$ are placed in the ray path. At a certain orientation of the plate with respect to the crystal, one can divide spatially two polarized rays.

The use of the half-wave plate provides a change in the direction of circular polarization and also changes the position angle of the linearly polarized radiation. If the phase shift is only slightly dependent on the wavelength, then the phase-shifting element is called achromatic. The most successful achromatic device is the Fresnel rhomb, where full internal reflections provide a phase shift of $\pi/2$. The exit rhomb returns the ray to the optical axis (Kizel et al. 1964). The disadvantage of the device is its large optical thickness. Another, more widespread method consists in combination of properties of positive and negative crystals. Such phase-shifting elements operate in a wide range of incidence angles. The improvement of achromatic phase-shifting elements is due to increasing number of crystal components (Pancharatnam 1955). The residual "non-achromatism" can be allowed for by a special procedure of observations.

In polarimetric investigations of astrophysical objects, the accuracy of measurements is limited by the instability of instrumentation and atmosphere. To diminish their affect, at the epoch of using one- and two-channel systems, modulation methods have been developed. These are varieties of a differential method in which the flux is modulated with a high frequency and the intensities of two orthogonally polarized rays change alternatively. The operation of the modulators is based on the electrooptic effect of Kerr: the crystals in an electric field from monoaxial become beaxial, the new axis being perpendicular to the field vector. The crystal with the surface perpendicular to the optical axis is covered with a grid of wire or semitransparent electrodes. When voltage of several kilovolts is fed, such an element can operate as a quaterwave plate at a wavelength depending on the voltage applied. The disadvantages of such a design (Pockels cell) is high voltage, low transmission, heating at high frequencies, operation only in parallel rays, different depth of modulation at different wavelengths. The enumerated demerits are basically overcome in piezooptical (photoelastic) modulators whose operation is based on the formation of a standing wave by means of excitation of acoustic vibrations in fused quartz.

The accuracy of measurement of polarization of radiation of astronomical objects is also limited by instrumental polarization (bright objects) and by the statistics of photocounts (faint objects). When observing with a telescope, the principal source of instrumental polarization is flat mirrors with metal coatings, the reflection from which gives rise to phase shift depending on the incidence angle. Reflection coefficients for orthogonally polarized components are different, therefore the reflection introduces instrumental elliptical polarization. The protective dielectric coatings on the mirror can also give instrumental polarization. Part of this linear polarization may transform into elliptical with subsequent reflections on the mirrors of the coude path. The variations with wavelength are weak, that is why, they would seem to be disregarded when measuring the Zeeman effect from a single line. However, this leads to diminishing the value of splitting σ components. Such a "decrease in contrast" is a function of angles of incidence on flat mirrors and wavelength, for this reason, a conclusion can be drawn that the accuracy of measurements of magnetic fields at the coude focus is basically limited. The methods of measurements and allowance for polarization caused by the coude focus mirrors can be found in the papers by Clarke (1973) and Borra (1976).

An altazimuth mounting of a telescope has some advantages over an equatorial one since it allows instrumental polarization to be taken into account by means of comparison of observations made before and after meridian (similar to that as it is done at the fully rotatable radio telescopes). Most polarimeters are designed for the Cassegrain foci, where instrumental polarization is insignificant (caused mainly by heterogeneity of mirror coatings). To eliminate this instrumental polarization when making systems of polarimetric standards, small Cassegrain telescopes of special design, where the mirrors could be rotated together with the tube about the main optical axis, were used.

3. Single- and two-channel polarimetric devices

The history of spectropolarimeters begins from the designs oriented to the use of single- or two-channel light detectors. Hiltner (1951) showed that the noises caused by the terrestrial atmosphere are coherent for the orthogonally polarized components. This circumstance forms a foundation for two-beam layouts — when measuring the ratios of two signals, the change in transparency and flickering effects compensate. The use of photomultipliers ensured sufficient time resolution, for instance, in searching for magnetic fields in fast-rotating white dwarfs. The necessity for making differential measurements, i.e. providing a fast phase shift, has lead to using electrooptical modulators developed earlier for a solar magnetograph (Babcock 1953). We consider the magnetometer of Angel and Landstreet (1970) developed to the search for the Zeeman effect in the hydrogen line H_γ in the spectra of white dwarfs to be the base model of the two-channel polarimeter. The electrooptical modulator and the Wollaston prism operate in a collimated beam, interference filters (30 Å pass-band) are positioned in the beams diverging after the prism. Next, the Fabry lenses and the photomultiplier are installed. The change of the sign of voltage applied to the modulator leads to the fact that along the Wollaston prism axis the radiation having now right now left polarization turns out to be linearly polarized. The change in the tilt of the filters makes it possible to rearrange their pass-bands toward adjacent fragments of the line profile. Such a design was subsequently used in searches for surface magnetic fields in bright stars (Landstreet et al. 1975) at telescopes of different diameters: 0.6 m Columbia Univ., 1 m KPNO, 1.2 m Western Ontario, 1.5 m MtWilson, 2.1 m McDonald with filters of pass-band of $\Delta\lambda = 1.5$ Å and $\Delta\lambda = 20$ Å. A search for surface magnetic fields in stars brighter than 5^m to declinations above $-20°$ was performed (Borra and Landstreet 1980). A standard error of 300 G of measuring magnetic field was achieved during an hour integration of the signal from a 5^m star at the 1.2 m telescope. Note for comparison that the error of such an order was obtained at larger telescopes from photographic Zeeman spectra only for stars with narrow lines (Preston 1969).

In the late 60s the methods of solar magnetography (Babcock 1953) were implemented in Crimean Astrophysical Observatory for observations at the coude focus of the 2.6 m telescope (Severny 1970). An electrooptical modulator (130 G) and polaroid were placed in front of the entrance slit of the spectrograph. With the photomultiplier installed behind the movable exit slit (reciprocal linear dispersion 1.5 Å, the step of slit displacement 0.2 Å) the difference in intensities between the clockwise- and counterclockwise-polarized components of the line was measured. Borra and Landstreet (1973) developed the method designed by Severny (1970) through adding the polarimeter by a Soleil-Babinet compensator of instrumental polarization and using Glan-Thompson prism as a polarizer. In long-time acquisitions taken with the 2.5 m telescope an accuracy of 3 G and 30 G was achieved for stars of 2^m and 7^m, respectively.

The two-channel narrow-band scanning polarimeter designed at the observatory of Glasgow University was used at the telescopes of diameters 0.51, 0.91 and 2.5 m (Clarke and McLean 1975). The device based on rotating half-wave plate and Foster prism was intended for measurements of linear polarization, while for measurements of circular polarization a quarter-wave plate was placed in front of the half-wave plate. Turn of the axes of the quarter-wave plate with respect to the polarizer axes was 45°. The interference filters with a pass-band of 50, 25, 10 and 2.5 Å were positioned in the collimated beam. The wavelength scanning was performed by the tilt of the filter to the axis of the beam.

The single-channel spectropolarimeter intended for measuring linear and circular polarization was designed in Edinburgh observatory (Wolstencroft et al. 1983). A photoelastic modulator representing a plate of fused quartz providing a phase shift at a frequency of 5 kHz was used in the device. For linear polarization measurements, two quarter-wave plates were alternatively inserted before the modulator, when measuring circular polarization the plates were removed. The modulator is followed by the analyzer the axes of which could take two positions differing by 90°, both positions are separated by 45° from the axis of modulator compression. The device can be rotated as a unity in position angle. The polarimeter is constructed on the basis of the spectrometer, which itself is a crossed Czerny-Turner design, the scanning was made by rotating a flat diffraction grating. A two-lens Fabry system is installed at the exit in front of the photomultiplier. The range of spectral resolutions from 5 Å to 400 Å is provided by three changeable gratings and changeable entrance diaphragms of different diameters.

A successful combination of the two-channel counting system with the high resolution spectropolarimeter was made by Borra and Vaughan (1977). The basic element of the spectropolarimeter is the electrooptical modulator (EOM), which when electrically powered, operated as the quarter-wave plate, that is, it converted circularly polarized light into linearly polarized. The Glan-Thompson prism is a linear polarizer and transmits light of particular polarization into the spectrometer. The axes of the prism are oriented at an angle of 45° relative to the “fast” and “slow” axes of the EOM. The frequency of alternating the voltage sign in the EOM leads to the fact that the spectrometer catches radiation now with left now with right circular polarization. To eliminate the effects of drifts of sensitivity, transparency, seeing, the frequency of switching the EOM was 1000 Hz. When observations are made at the coude focus, it should be taken into account that due to the reflection on flat mirrors, additional phase shift and additional polarization appear. For stars in the interval of declinations from $-10°$ to $+50°$, instrumental linear polarization at the coude focus of the 2.5 m telescope changed from 2 to 8 %. It can be significantly reduced by using the compensator of instrumental polarization. For instance, Borra and Vaughan (1977) installed in front of the EOM a Soleil-Babinet compensator operating in the beam F/30. To increase the relative aperture of the scanner at its exit (F/19), a tunable Fabry-Perot etalon was installed in front of one photomultiplier (Voughan, Zirin 1968), the second photomultiplier registered the flux in two fixed bands (each being 25 Å) located on both sides of the region being scanned.

Correlation spectrometers with a multislit mask (see, for instance, Griffin, Gunn 1974) became efficient spectral instruments combining the light detectors (photomultiplier) and the principle of multiplicity (Felgett 1955). Based on one of such a correlation meter of radial velocity (McClure et al. 1980), a multislit photoelectric magnetometer (Borra et al. 1981) was created. The crystal of the electrooptical modulator with a modulation frequency of 100 Hz installed behind the Glan-Thompson prism operates as switchable quarter-wave plate. At first, the spectrometer was used in the mode of measuring radial velocities with the aim of specification of the mask position. Then for selection of sequential positions of the mask polarimetric measurements are made. The used telescope (1.2 m) had earlier been optimized for spectroscopic observations at the coude focus (Richardson et al. 1971). In particular changable flat mirrors with dielectric coatings were used. All the coatings developed for the blue region of spectrum proved to be incompatible with the problem of spectropolarimetry, whereas the mirrors with silver coating showed low instrumental polarization.

The design of the hydrogen line magnetometer of the 6 m telescope (Shtol et al. 1985) develops the method proposed by Angel and Landstreet (1970). Instead of interference filters isolating portions of hydrogen line wings, a commercial diffraction spectrograph with a mirror-lense and then with a lens camera (slit-scale factor turned out to be less than unity in both cases) was used. The device was intended mainly for measuring circular polarization in the wings of hydrogen lines. The improvement of the device made it possible to make simultaneous measurements in the wings of two hydrogen lines. Since 1988, the device has been used for linear polarization measurements as well. Then an original set-up of combination of the polarimetric analyzer with the polichromator was proposed (Shtol 1991), but the epoch of use of photomultipliers on large and medium telescopes already ended.

A 33-channel spectrophotometer of Oke (1969) designed for the Cassegrain focus of the 5 m telescope proved to be transitional between single-channel, two-channel and multichannel systems. A double diaphragm was placed at the entrance of the spectrometer. The diaphragm apertures were shutted alternatively (‘object plus sky’ and ‘sky’), the recording of the corresponding spectra on the photomultiplier strip was performed interchangeably. The modification of the spectrophotometer to the spectropolarimeter was carried out in the following manner (Angel et al. 1972). A beam of F/16 was collimated with a negative lens located above the cell of the electro-optical modulator. The Glan-Thompson prism with the orientation of the axes making an angle of 45° relative to the axes of the cell was positioned above the double diaphragm of the spectrophotometer. Instead of diaphragm apertures, the modulator was switched every 10 seconds, and components of spectra of left and right circular polarization fall on the photomultiplier strip alternatively.

4. Multichannel systems of low and medium resolution

The introduction of multichannel electronic semiconductor light detectors into astrophysical practice has qualitatively changed the spectrophotometric equipment. From the systems in which the scanning of a spectrum was performed mechanically by means of movement of one of the elements of the spectrometer (rotation of the grating, movement of the entrance slit or a mask of slits, vibration of the transparent plate behind the entrance slit, rotation of interference filters etc.), astronomers changed over to spectrographs, where on the light sensitive element strip a radiation of a wide range of wavelengths was recorded at once. A gain in the slit-scale factor was realized in addition. In contrast to spectrophotometers with photomultipliers having a slit-scale factor of about 1, the use of new light detectors with a small size of the resolution elements led to the introduction of layouts with the decrease of the scale at the detector entrance. Thus, the changeover to the multichannel systems, apart from the apparent advantage in the number of spectrum elements recorded simultaneously and change to noises of other nature, provided a gain in flux. This, in combination with increasing sensitivity of light detectors, allowed elaboration of a new class of devices — multichannel spectropolarimeters. However, the possibility of recording in a narrow (in comparison with the filter polarimeter) spectral range demanded to take additional measures to improve the accuracy of polarimetry and in the seventies modulational multichannel methods was practised on a large scale. Several examples can characterize the technology of this period.

The development of the Lick spectropolarimeter can serve as an example of successive combination of the modulation technique with the multichannel light detector. At first the main component of the system was the Robinson–Wampler scanner (Robinson, Wampler 1972), where a dissector system with a brightness amplifier was used as light detector, which permitted simultaneous recording of spectra of the object and background on two strips. The first step in the transformation of the scanner into a spectropolarimeter was made by Nordsieck (1974) by placing crystallo-optical filters after the slit (in succession: a quartz with a thickness $d_1 = 1\,\mathrm{mm}$, a quartz $d_2 = 3\,\mathrm{mm}$ thick, polaroid). The phase shift is adopted to be large, $\tau \gg 2\pi$, but not insomuch that $\sin\tau$ and $\cos\tau$ to change significantly within the scanner pixel (7 Å). In this case Q and V Stokes parameters can be determined through Fourier analysis of the intensity of radiation which passed the second phase plate and polaroid:

$$I'(\lambda) = [I(\lambda) + Q(\lambda)\cos\tau_2(\lambda) - V(\lambda)\sin\tau_2(\lambda)]/2,$$

where $\tau_2(\lambda) = 2\pi \cdot \Delta n \cdot d_2/\lambda$.

If the first phase-shifting plate d_1 thick is inserted, the intensity after such a three-element filter equals

$$\begin{aligned} I'(\lambda) = [&I(\lambda) + Q(\lambda)\cos\tau_2(\lambda) + \\ &+U\sin\tau_2(\lambda)\sin\tau_1(\lambda) - \\ &-V\sin\tau_2(\lambda)\cos\tau_1(\lambda)]/2. \end{aligned}$$

The ratio of thicknesses d_1/d_2 is accurate to 0.002 so that the ratio of frequencies $\tau_2-\tau_1, \tau_2, \tau_2+\tau_1$ is 2:3:4, which made it possible to simplify the computation of the Fourier transformation and operate on-line with the computer PDP-8. The film polaroid might be replaced by a polarization prism, this would increase the quantum efficiency of the polarimeter by 20 %. The following has an effect on the width of the instrumental function of the scanner in the polarimeter mode:

- operation of the quartz plates in convergent beam F/17 leads to shifts of bands formed by different zones of the beam by ±1 Å irrespective of the thickness of quartz;
- change in temperature by 4° causes a shift of bands by 2 Å, which is allowed for via calibration by sources with correct measured linear polarization;
- quasiperiod of variation of the value of $\sin\tau_2(\lambda)$ — from 25 Å at 3100 Å to 175 Å at 7500 Å (for linear polarization), and slower variations of $\sin\tau_1(\lambda)$ — from 75 Å in the UV to 500 Å in the red region (when circular and linear polarization are present simultaneously).

To reduce the noises and influences of the lines the spectrum was also recorded without the polarimetric attachment, I(λ), and Fourier analysis of I′(λ)/I(λ) was made.

The scanner of Robinson-Wampler and the polarimetric attachment were first used with the spectrograph non-optimal for the 3 m telescope, that is why, a specialized spectropolarimeter (Miller et al. 1980) was elaborated soon. This device was one of the highly automatic overhead spectrographs (even the choice of one of the three diffraction gratings was made remotely). The polarimetric device developed by Nordsieck (1974) did not meet the requirements of spectrophotometry of extragalactic objects either in spectral resolution or photon efficiency. That is why, a new layout replicating the design tested on the polarimeters of Angel and Landstreet (1970), Schmidt et al. (1978) was elaborated. The collimating optics and the electro-optical modulator (Pockels cell) were placed above the double decker (openings for the object and background) and a pair of the Fresnel rhombs (operating as achromatic quarter-wave plates) and a block of calcite prisms splitting the image of the deckers were positioned immediately below it. A potential of ±2 kV was applied across the electro-optic crystal (potassium dideuterium phosphate) via gold-wire grids on the optical surfaces. Every second the potential changes the sign, so the crystal operates as a reversible quarter-wave plate. Upon passing through the crystal, linearly polarized light becomes right or left circularly polarized, depending on the relative orientations of the plane of polarization and the crystallographic axes. After passing through the Fresnel rhombs the phase shift between the beams was either π or zero, that is, light became linearly polarized in orthogonal planes. Four parallel spectra (two each of "object-plus-sky" and "sky") were imaged on the photocathode. The parameter of linear polarization Q was calculated. The entire spectropolarimeter assembly is rotated by 45° to measure the parameter U. To measure circular polarization a quarter-wave plate is inserted in the beam. The frequency of change of the parallel spectra is limited by the time-decay of the image tube phosphors (Schmidt 1979).

As an example of work performed with this variant of the device, name spectropolarimetry of the Herbig-Haro object H-H24 (Schmidt and Miller 1979), where, by the character of polarization, the region of formation of emission lines was localized.

The method of electro-optical modulation in combination with two-dimensional photon counter was used in the multichannel spectropolarimeter of the 3.9 m telescope AAT (McLean et al. 1984). In front of the modulator (operating in a parallel beam) two quarter-wave plates (turned at 45° relative to one another) and the film polarizer (for the purpose of calibration) are placed. The block of calcite is located behind the slit of the spectrograph RGO. Instrumental polarization is insignificant and the accuracy is limited by the statistics of photons alone.

For the spectrograph of medium resolution (SP-124) with the photon counter, installed at the Nasmyth focus of the 6 m telescope BTA, I.Naidenov developed a circular polarization analyzer consisting of sequentially installed entrance quarter-wave plates, Rochon prism, an exit quarter-wave plate and a wedge compensating the deflection angle of one of the beams (Borisov et al. 1989).

The introduction of CCDs led to a gain in quantum sensitivity (by more than a factor of 7 in the case of Lick spectropolarimeter) and to an increase in the readout time, that is why the technology of modulation at relatively high frequencies with simultaneous readout had to be abandoned. The third version of Lick spectropolarimeter (Miller et al. 1988) is based on the use of two configurations of the spectrograph: "lens camera plus grism" for the range 4000–8500 ÅÅ and "UV spectrograph with the Schmidt camera" for the range 3000–11000 ÅÅ. At first Pockels cell was used as a modulator, while a CCD served for the intermediate storage of the signal. The latter became posssible due to the development of techniques of "scanning with shift". The pixel-by-pixel sensitivity of the first CCDs differed markedly, for this reason, a method of the shift of the collected charge synchronously with the image on the matrix was proposed (Mackay 1982). Since that time the method has been widely used in scanning the sky with the fixed telescopes. Triphase CCDs enable switching of the shift direction of the collected charge. The scheme of operation of the CCD with the modulator of polarization is as follows: the image is recorded by one and the same group of neighboring rows of the matrix, then the collected charge is shifted up or down. When the modulator restores its former state, the charge collected earlier returns to the zone of acquisition. It results in two tracks of spectrum integrated at different states of the modulator. The influence of inhomogeneity of the matrix elements in this mode is excluded. The switching of the modulator and corresponding accumulation of signal in the Lick spectropolarimeter was realized in an interval from 200 ms to a few seconds.The use of the scanning with a shift revealed limiting factors: without income of the light signal the dark signal largely increased even at shifts, and the presence of charge storage state in the zone of scanning caused deterioration of the signal. It was concluded that the effects indicated make the method of shift of images unsuitable for high accuracy work.

The employment of the first CCD showed high recurrence of calibrations. Since the necessity for modulation with high frequency was called in question, the method of observations with the Lick spectropolarimeter changed. The accumulation of signal (with subsequent readout) with the unchanged state of the modulator was carried out in the mode of slow modulation (phase switching once per several minutes). But when the cell was kept for several minutes at a constant potential, its optical transmission considerably dropped. The development of the method of slow modulation caused full refusal from the modulating cell replaced by rotation of the spectropolarimeter about the optical axis of the telescope (i.e. by changing the position angle). The calcite crystal located behind the slit produces two perpendicular polarized monochromatic images of the slit registered simultaneously. The four exposures made at the position angles of the spectropolarimeter differing sequentially by 45°, are sufficient for measuring linear polarization. The disadvantage of the method is lowering the accuracy of determination of the Stokes parameters because of the bend of the instrument (one and the same element of the spectrum registered at different orientation of the spectrograph and analyzer of polarization falls at different CCD pixels having different sensitivity).

The next step in the development of the method of slow modulation was the use of rotating wave plates. The half-wave achromatic plate is placed in front of the slit and consists of a set of thin polymer films confined between two quartz protective glasses. The 'fast' axes of each film are turned relative to one another so that the total shift to half wave is attained for the range 3200–7200 Å with an accuracy of a few per cent. When the value of the position angle of the spectropolarimeter and of the axes of the calcite crystal located behind the slit, four exposures are made at different orientation of the axis of the half-wave plate ($0^\circ, 45^\circ, 22.5^\circ, 67.5^\circ$). The Lick spectropolarimeter thus improved was used mainly for measuring linear polarization.

Goodrich (1991) designed achromatic polarization optics for the Cassegrain spectrographs of the 2.7 m telescope of McDonald and the 5 m of Hale. A superachromatic half-wave plate and a modified prism of Glan-Taylor are employed. The air space, the orientation of axes and the values of the angles of the prism were chosen so that an extraordinary ray passes the air space between the components of the prism and travels along the axis of incidence of light, whereas the ordinary ray after double full internal reflection in the prism comes out of the prism parallel to the axis.

The necessity to search for soft magnetic ($B_e <$ 1 MG) white dwarfs forced to change from using the effect of photospheric dichroism in measurements of circular polarization in the continuum (Kemp et al. 1970; Angel et al. 1981) to the application of the linear (Angel et al. 1981) and quadratic (Preston 1970) Zeeman splitting. To make a survey of white dwarfs with effective fields 1 MG> B_e > 10 kG, a spectropolarimeter, suitable for medium size telescopes, was created at Steward Observatory (Schmidt et al. 1992).The small diameter of the collimated beam (25 mm) made it possible to place a Wollaston prism after the collimator F/9. The phase-shifting half-wave or quarter-wave plates are inserted behind the slit in turn, possibility of their rotation is available. The diffraction gratings 1200 and 600 lines per mm in combination with the objective F=50 mm enables operation with a resolution of 7 and 13 Å, respectively. The weight of the cryostat and controller of the CCD makes a considerable part of the total weight of the device (50 kg). The magnetic field was detected from the S-shaped profile of V parameter of circular polarization in the region of the lines H_α and H_β.

For the spectrograph LRIS of the 10 m telescope Goodrich et al. (1995) used the modification of Glan-Taylor prism compensating the mismatch of the positions of the focus for the ordinary and extraordinary rays (it will be recalled that the collimator of LRIS has no means for focusing).

For the investigation of interstellar and circumstellar polarization, Kawabata et al. (1999) developed a spectropolarimeter HBS with low resolution (R=40–200). The device used at the 0.9 m (F/18) telescope of Dodaira Observatory consists of two parts. The first one is a classical polarimeter (turret of diaphragms, collimating lens, rotating half-wave plate, Wollaston prism, quarter-wave plate, exit achromatic lens). The second part contains the details of the spectrograph (slit, mirror collimator, diffraction grating 300 gr/mm, lens camera). The CCD recorded four tracks of spectra (two from the object and two from the sky background). Apart from spectrum sources, the calibration unit contains Glan-Taylor prism. Observations are made in four sequential positions of the axis of the half-wave plate (from 0 to 67.5°). The observations with the HBS is an example of optimized approach to spectropolarimetry with high spatial resolution at small telescopes.

Part of the programs of spectropolarimetry with high spectral resolution performed at SAO with the 6 m telescope needs to be supported by spectropolarimetric methods of moderate resolution. For this purpose, in the Laboratory of spectroscopy of stars manufacturing of a moderate resolution spectropolarimeter for the Cassegrain focus of the 1 m telescope of SAO is being completed. The device will measure linear polarization in a wavelength range of 3900–9000 ÅÅ with a spectral resolution of R=700–2800.

5. Multichannel systems of high resolution

Spectropolarimeters of high resolution are intended to investigate polarization effects in narrow spectral intervals, in particular, line profiles. Babcock (1947), who was the first to measure the Zeeman splitting of lines with the coude focus spectrograph with a narrow-band quarter-wave mica plate and iceland spar crystal, was the pioneer in this work. Ten years later the number of stars investigated in this manner was above three hundred (Babcock 1958). At the same time the creation of achromatic phase-shifting plates was started (Pancharatnam 1955). The measurement accuracy of the Zeeman effect for stars with narrow lines was determined mainly by the number of measured magnetosensitive lines. In the late 60-s it was shown that in the problem of searching for magnetic fields of large and medium strength one can restrict oneself to the estimation of the field from the splitted Zeeman components or from the broadening of magnetosensitive lines, i.e. to record spectra with reciprocal linear dispersion 3–5 Å/mm without using spectropolarimetric devices (Preston 1971). It turned out, however, that from the splitted Zeeman components, the strength of the effective magnetic field considerably differs from the estimates obtained by the method of unsplitted components (Babcock 1960).

Magnetic fields of stars has been studied at SAO RAS for more than 25 years for which the Main stellar spectrograph of the 6 m telescope has been used. An achromatic analyzer of circular polarization is placed in front of its slit, in which the phase shift is insured by reflection from the surfaces of Fresnel rhomb (Naidenov, Chountonov 1976a). This analyzer was designed for photographic recording of spectra. To provide equality of darkenings and to return the splitted beam to the optical axis a second Fresnel rhomb was installed converting the linearly polarized light (after passing the Island spar) into circularly polarized.

At the present time the desire to increase the number of magnetosensitive lines recorded simultaneously, preserving high spectral resolution, made address to the development of polarimetric devices for echelle spectrographs. The first attempt of combination of the circular polarization analyzer with the Cassegrain echelle spectrometer (Anderson et al. 1976) demonstrated the method to be promising and served the basis for use of the circular polarization analyzer on the Cassegrain echelle spectrograph of the 4 m telescope of KPNO (Anderson and Nordsieck 1978). This instrument follows the design developed by Babcock: two circularly polarized σ components of a line are transformed by a quarter-wave plate into linearly polarized light emerging from the phase-shifting plate at an angle of ±45° to its fast axis. Then the calcite plate provide spatial division of these components. Having no possibility of introducing serious changes into the echelle spectrograph of general use, Anderson and Nordsieck (1978) placed the quarter-wave plate in the preslit turret, while the calcite plate was put in the turret behind the slit. For the work with the reticon a wider division of the component than in the case of photographic work is needed. In this case another calcite plate (43 mm thick) was employed. The defocusing due to different optical paths of the components of the polarized radiation was insignificant in the case of photographic recording through an image tube and is noticeable when working with the reticon.

Vogt et al. (1980) essentially improved the technique of obtaining Zeeman spectra at the coude focus. In the preslit part there sequentially placed the Soleil-Babinet compensator and the achromatic quarter-wave plate cemented with the calcite block. The phase shift arising on flat mirrors of the coude path is a function of hour angle, declination, wavelength, that is why the mechanism of the compensator of instrumental polarization is equipped with a stepping motor controlled by computer commands.

Mathys and Stenflo (1986) adapted the Cassegrain echelle spectrograph (CASPEC) of the 3.6 m telescope of ESO for the simultaneous recording of the Stokes parameters I and V in the range 100 Å with a resolution of R=20000. This made it possible to use "multiple line approximation" developed for diagnostics of the fine structure of the magnetic field of the Sun (Solanki and Stenflo 1984, 1985; Stenflo et al. 1984). The Zeeman analyzer consisting of the quarter-wave plate and Wollaston prism (diverging the beams by 1°) are placed immediately after the slit, and the radiation passing through these elements was collimated by the lenses.

It is not infrequent that the systems of high resolution are located in the coude or Nasmyth focus. In the attempt to employ such devices as spectropolarimeters in both cases there is a necessity for taking account of instrumental polarization on the flat mirrors of the telescope. It is attempted to solve this problem by different methods, let us dwell on some technical approaches.

Babcock (1962) used compensators of instrumental polarization arising on three and five mirrors of the coude focus of Hale telescope. Recall the experiments of Clarke (1973), Borra (1976), Vogt et al. (1980). Pillet and Almeida (1991) proposed a two-mirror layout of the telescope with the coude focus, free from instrumental polarization. The effect is achieved by placing the half-wave plate between two identical flat mirrors. It is shown that for the vacuum solar telescope (Gregory-Coude scheme) instrumental polarization can be compensated to an accuracy of 0.2 %.

On the echelle spectrographs of the Nasmyth focus of the 6 m telescope of SAO, for high resolution spectropolarimetry half-wave and quarter-wave achromatic plates in conjunction with the achromatic analyzer of circular polarization (Naidenov and Panchuk 1996) are used.

One of the methods to exclude instrumental polarization is the use of the layout "polarization analyzer – optical fibers – spectrograph". We adduce several examples of coupling the polarization analyzer with the spectrograph. The task of Zeeman-Doppler mapping of fast rotating stars requires a signal/noise>1000, high spectral resolution (R>40000), relatively short exposures and low instrumental polarization. The using of the Cassegrain echelle spectrograph at the 4 m-class telescopes seems to be ideal, however such telescopes are seldom used for monitoring tasks. Semel et al. (1993) have demonstrated the ways of solution of this problem on three telescopes. The spectrograph ISIS (Felenbok and Guerin 1988) was used on the 1.93 m telescope OHP in 1986–1989. In the end they came to the conclusion that the fiber-optic coupling of the spectropolarimeter and the spectrograph is efficient, but for the mapping of stars with narrow lines in spectra the telescope with such a mirror diameter is insufficient. The spectrograph RGO (resolution R=40000 with a slit of 0.6″) was used at the AAT in 1989–1990. For CFHT (observations of 1990) the structure was added by a double image slicer of the type of Bowen-Walraven, which was placed at the outlet end of the optical fiber and consisted of two microprism, plane-parallel plate and main prism.

With the aim of making coordinated observations with spectrographs of one and the same type but spaced apart in longitude, at the end of the 80s a relatively inexpensive echelle spectrograph MuSiCoS (Baudrand and Bähm 1992) was developed. The MiSiCoS design permitted it to be installed on different telescopes of the 2 m-type (three devices were placed on the 2 m telescope TBL at Pik du Midi Observatory, the 2.5 m telescope INT at La Palma Observatory and the 1.9 m at the South African Astronomical Observatory). A star image was transferred from the Cassegrain focus of the telescope to the slit of the spectrograph through optical fibers, the resolution was R=35000. Investigations of peculiar stars revealed a need to fit MuSiCoS with additional polarimetric devices (Donati et al. 1999). The design of the Cassegrain adapter allows operation with different relative apertures. The ratio F/25 (characteristic of TBL), not typical of a Cassegrain focus, was taken as the basis. Behind the entrance aperture a doublet is placed, which matches the relative aperture of the Cassegrain focus with the chosen ratio. Then sequentially follow the turret with the film polaroids, the turret with the half-wave and quarter-wave superachromatic (range 3900–8700 ÅÅ) plates. The half-wave and quarter-wave plates can be rotated to fixed angles $0°, 22.5°, 45°, 67.5°$ and $-45°, 0°, 45°$. An experience has shown that the turn of the polarimetric head as a unit through $0°, 45°, 90°, 135°$ is a more preferable procedure than the rotation of the half-wave plate. The phase-shifting elements are followed by the Savar plate consisting of two crossed calcite blocks. It diverges the beams to a distance equal to the minimum distance between two optical fibers. In front of the optical fibers the focal reducer, forming a beam F/2.5 is placed. The total efficiency of the spectropolarimeter is 0.8 % at a maximum sensitivity of the CCD. To reveal variations of polarization within the line profile a method of formation of the "averaged polarization property" is applied (Donati, Cameron 1997).

The spectropolarimeter of the University of Western Ontario (Eversberg et al. 1998) was designed for Cassegrain foci (F/8) of telescopes of medium and large diameters. The spectropolarimeter is a combination of two rotating quarter-wave plates operating in a parallel beam and a fixed Wollaston prism with subsequent introduction (F/4) of the ordinary and extraordinary beams into the fiber optic line the exit of which is coordinated by lenses with the slit spectrograph (F/8). The quarter-wave plates provide an ideal shift only for two wavelengths. For the calibration of the orientation of these plates the Glan-Taylor prism is used, which provides 100 % linear polarization in the entire range of operation of the spectropolarimeter.

Thus, the problem of fiber optic coupling of the analyzer and spectrograph for telescopes of class 2–4 m has been solved. The employment of fiber optic spectropolarimetric methods of high resolution for large telescopes is restrained by the problem of slit-scale factor. We will illustrate this by the example of BTA. Suppose that at the prime focus (F/4), after the entrance diaphragm a parallel beam first forms, which is splitted through the polarization optics, then the split beam is projected (F/2.5) on a pair of optical fibers with a core diameter of 0.15 mm, which corresponds to $2''$ on the celestial sphere. The exit of the pair of the optical fibers is at the entrance of the collimator (F/2.5) of the echelle spectrograph, the necessary feature of the fiber optic spectrograph being the absence of the central screening. Assuming that the camera F/2 is used (more large aperture ratio cameras are unsuitable because of the PSF, unstable over the field), then the pixel size in the focal plane will be 0.12 mm. This means that for the pixel size to match that of the light detector, it is necessary to use a double image slicer at the exit of the optical fibers, which would provide three slices for every optical fiber. That is, one echelle order will be repeated 6 times (three times in each polarization). The projection of each slice will be 0.04 mm, and to implement the resolution R=50000 with the echelle R2 a camera with a focal distance not less than F=480 mm will be required, i.e. the diameter of the collimated beam will be 240 mm, and the length of the grooved area of the echelle will be about half a meter. Since the number of the simultaneously recorded echelle orders is restricted by the use of the slicer, then for the simultaneous recording of a great number of magnetosensitive lines, it is desirable to have a camera with a large enough field (intended for a light detector with dimensions of 2048×2048 pixels). The fabrication of a lens camera with such characteristics is rather complicated and expensive.

If in a number of problems of spectropolarimetry the value of the required spectral resolution is such that it can be provided with a compact spectropolarimeter of the prime focus of BTA, then such a solution seems to be optimal. As an example, we give experience of renovation of the echelle spectrograph of the prime focus PFES (Panchuk et al. 1998), resulting in a device for measuring linear polarization with the spectral resolution R=13000 (Panchuk et al. 2001b)

6. Spectropolarimetry with Fabry-Perot interferometer

Advantages of the Fabry-Perot etalon over the diffraction spectrograph are known (higher value of the product of relative aperture L by the resolution R). That is why, as early as at the epoch of single-element light detectors, there appeared the first spectral systems in which the high value of L×R was combined with the main merit of diffraction spectrograph — spatial division of light with different wavelengths. In the single-channel recording, the process of retuning of the etalon placed at the entrance of the spectrometer must be accompanied by coordinated movement of the exit slit along the spectrum. This method tested in practice by Geake and Wilcock (1957) was used then at the 2.5 m (Vaughan and Münch 1966) and at the 5 m (Zirin 1966) telescopes. To search for and measure weak longitudinal magnetic fields at the 6 m telescope a photoelectric magnetometer with a tunable Fabry-Perot etalon was used (Glagolevsij et al. 1979). A monitoring circuit for interferometric check of variation of pressure of gas between the plates of the etalon is used in the device (Naidenov and Chountonov 1976b). For the recording of the two-dimensional pattern of solar magnetic fields, a tunable birefringent Fabry-Perot interferometer was created (Ramsey and Smartt 1966). In front of the etalon a quarter-wave plate converting the circularly polarized components into linearly polarized was situated. A mica sheet was inserted between the plates of the etalon. The thickness of the mica plate defined the phase shift between orthogonally polarized spectra. Rotation of the quarter-wave plate changes the sign of circular polarization, but does not modulate unpolarized or linearly polarized light. In the solar magnetometer the etalon was tuned to the wing of a magnetosensitive absorption line, that is why, the polarization optics may be nonachromatic. The difference of consecutive two-dimensional intensity distributions recorded in the line wing at different positions of the axis of the phase-shifting plate represents a map of the distribution of the magnetic field longitudinal component, and to a first approximation is independent of Doppler shifts.

In spectropolarimetry of point objects with multielement light detectors, it is possible to record several orders of the etalon simultaneously. The introduction of high sensitivity two-dimensional multielement detectors has widened the possibilities of combination of the Fabry-Perot etalon with the high-resolution spectrograph, in particular, there is an example of simultaneous recording of several hundred etalon orders. As a development of the method of doubly crossed dispersion it is interesting to consider a case of combination of the Fabry-Perot interferometer and the circular polarization analyzer. Fig. 1 shows a fragment of the echelle spectrum of a star, which we recorded with the Nasmyth echelle spectrograph (NES) of the 6 m telescope (Panchuk et al. 1999). On the preslit part of the device were placed sequentially the circular polarization analyzer and Fabry-Perot etalon. With such a set-up the light divided into right- and left-rotating component, passes through the etalon and encounters the double entrance slit of the spectrograph. In this case the echelle spectrograpf serves only for spatial division of the etalon orders. Comparison of intensities of the orthogonal components of light in orders falling on the wings of magnetosensitive lines can reveal the difference of the profiles, which is caused by the Zeeman effect. This method of fixing (and also scanning) wavelengths may prove to be useful for the development of diffraction spectropolarimeters subject to positional instabilities, or limited in the class of diffraction devices by the invariant L×R.

7. Conclusions

It is shown above that as the requirements to the accuracy of polarization measurements become more stringent, spectropolarimetric observations of stars "drift" towards larger telescopes embracing the measurement of all Stokes parameters. We associate further use of devices and methods for spectropolarimetric studies of stars at the telescopes of SAO with the following directions:

- development of methods of compensation (taking account of) of polarization caused by the flat mirror of BTA;
- development of a method of compensation of field rotation at the Nasmyth focus not producing variable instrumental polarization;
- elaboration of a high resolution spectropolarimeter for the prime focus of BTA;
- search for engineering solutions of fiber optic connection of the polarization analyzer at the prime focus of BTA with the spectrograph in which the central screening of the beam is absent;
- development of a spectropolarimeter of moderate resolution for the Cassegrain focus of the 1 m telescope;
- quest for possible combinations of the polarization optics with the Fabry-Perot etalon in the BTA echelle spectrographs.

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