Polarimetry at the NOT

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Abstract. The observational techniques available for polarimetry at the NOT are reviewed. Examples of the research carried out are shown. Some prospects for future work are discussed.

1. Introduction

Polarization of light provides information which is particularly useful for determining the geometry of the light emitting source, and the radiation processes involved. Mechanisms such as scattering by small dust particles or free electrons, or various absorption and emission processes in a magnetic field, produce polarized light. Studies of the amount and direction of the polarization as a function of wavelength and time may help to establish a physical and geometrical model which can reproduce the observed polarization behaviour.

2. Observational techniques

2.1. Simultaneous UBVRI polarimeter (Turpol)

The instrument is a new version of the Simultaneous five-colour (UBVRI) polarimeter (Piirola 1973, 1988; Korhonen, Piirola, and Reiz 1984) extensively used for studies of interacting binaries and circumstellar matter since 1981 at Crimea and at La Silla. The double image chopping measuring technique provides inherently very good stability and enables polarization levels below 0.01 percent to be detected.

Simultaneous measurements of both circular and linear polarization in five colours can be obtained by using a rotatable achromatic (300-1100 nm) quarter-wave retarder in front of the calcite plate, as the polarization modulator. For measurements of linear polarization with the best efficiency a half-wave retarder is used. The instrument is changed to a multichannel sky-chopping photometer by removing the calcite block from the beam.

The calcite plate polarizing beam spitter yields direct elimination of sky background polarization. This has been found especially valuable in the observations of faint stars and in the moonlight. If a considerable amount of the background radiation is composed of scattered light, it can be highly polarized and very small relative changes in the sky background could cause large errors in the measured stellar polarization. Also the very small value of systematic errors obtained for brighter stars (e(p) $\sim$ 0.005 %) probably is in part the result of the effective cancellation of the background polarization.

As the signal to noise ratio required in polarimetry is high, usually S/N$\geq$1000, sufficiently large numbers of photons have to be collected in each measurement. Hence the integration times are long for faint stars and especially multicolour polarimetry becomes time consuming. In order to increase the efficiency it was considered important to enable simultaneous measurements in several wavelength bands. Also for rapidly variable objects strictly simultaneous observations in different colours are essential.

The colour bands are separated by dichroic filters which reflect the desired spectral interval and transmit the other wavelengths. By using four of such selective beam splitters, the light is divided into five photomultipliers for simultaneous recording in the UBVRI bands. The efficiency is high as there is practically no internal absorption in the dichroic filters. The design goal has been a good throughput and the instrument has been optimized for observations of faint and variable objects.

The time resolution in photometry is two seconds. In polarimetry, where 8 integrations are made in the chopping mode and some on-line reductions are required, the highest time resolution is about 1 min. For the simultaneous photometric data obtained during polarimetry the time resolution is 5 s.

2.2. Imaging polarimetry, spectropolarimetry

The ALFOSC focal reducer/spectrograph is a versatile instrument for imaging with a CCD detector, and provides also spectrographic capabilities. The dispersing element (grism) is inserted into the collimated beam before the re-imaging camera optics.

Imaging polarimetry can be carried out with ALFOSC in the following basic configurations:

1. Two calcite plates in the slit wheel, with 45° difference in their orientation (linear polarimetry).
2. One calcite plate + fixed quarter-wave-plate in the slit wheel (circular polarimetry).
3. One calcite plate in the slit wheel + rotatable half-wave-plate in the FASU=Filter And Shutter Unit (linear polarimetry).
4. Four Polaroid sheets with orientations 0° 45° 90° and 135° in the FASU unit (linear polarimetry).

The technique 1. has been used for Blazar polarimetry at the NOT for objects fainter than about V=18, which is the practical limit for Turpol. It is suitable for point-sources, or extended sources of less than 15" apparent diameter, which is the distance between the two polarized images produced by the calcite plate (2mm). The ratio of the transmission coefficients of the two polarized beams has to be calibrated by a zero-polarization standard star.

The technique 2. has been used for circular polarimetry of magnetic cataclysmic variables which are too faint for Turpol, and for circular spectropolarimetry. It is convenient way of observing, as there are no moving parts for polarization modulation. The null calibration is needed as in point 1. above.

The technique 3. is the optimal way to carry out linear polarimetry. Rotating the half-wave-plate in 22.5° steps will give the position angles 0° and 90° in the first exposure (through the fixed calcite plate), the next 45° and 135° , the following 90° and 180° , and the fourth 135° and 225° . With these eight images the ratio of the transmission coefficients of the two othogonally polarized beams, produced by the calcite plate, can be eliminated in the reductions.

The technique 4. yields wide-field imaging polarimetry (the full ALFOSC field of 6.5 arcmin), but wastes half of the light as one of the polarization components is totally absorbed in the Polaroid. It is also sensitive to atmospheric transparency changes between the exposures. However, for extended objects, like reflection nebulae around young stars in star forming regions, the Polaroid technique has been applied with success at the NOT (see e.g. Piirola et al. 1992, 1999).

Linear spectropolarimetry can be carried out with the technique 3. A grism is inserted into the collimated light path before the camera optics. Two perpendicularly polarized spectra are obtained in each position angle of the half-wave plate. Polarization parameters can be calculated for each desired wavelength interval in the spectra using the same basic formalism as in imaging polarimetry (see e.g. Piirola 1992). Minimum requirement is two exposures (null calibration required), but with four exposures the difference between the transmission of the orthogonally polarized spectra is eliminated in the reductions, as the polarization modulation of the o- and e-rays will have inverse effect in the 3rd and 4th exposure, as compared with the 1st and 2nd.

3. Studies of Interstellar polarization at the NOT

The classical example of polarization of starlight is the effect introduced by interstellar dust grains, aligned by the galactic magnetic field. The elongated grains rotate around their minor axis aligned with the field lines. Therefore, when looking perpendicular to the field, the projected size of the dust grains is larger in the direction orthogonal to the field lines, and the absorption coefficient of the respective polarized component of starlight is larger that that parallel with the field. Net effect is that the starlight traversing through interstellar dust coud is polarized, with maximum vibration parallel to the magnetic field. However, for viewing directions along the field lines, there is no preferred orientation of projected dust grains, and no net polarization, only absorption.

Berdyugin, Teerikorpi, and Snare (1995, 1997) have studied the amount and distribution of interstellar dust, and the galactic magnetic field structure, in the direction of the North Galactic Pole (NGP). The amount of dust in the Solar neighbourhood in the directions away from the galactic plane is small, but still has effects in e.g. photometric distance scale measurements, which are difficult to calibrate out. Polarimetry yields an absolute measurement of lower limit of extinction through an empirical relation. For detection of small extinction values polarimetry is more sensitive by a factor of about 10, as compared with photometric determinations.

The results from the polarimetry near the NGP are important also for improving the extragalactic extinction corrections applied at high galactic latitudes. The difference between competing extinction models has been one reason for e.g. the diverging Hubble constant determinations.

4. Scattering by circumstellar matter

While the imaging polarimetry of scattered light from the nebulae around young stars is a powerful tool to investgate the properties of the circumstellar cloud and possible protoplanetary disk (Piirola et al. 1992), polarization studies of the integrated light of unresolved (pointlike) objects can also provide information about the scattering envelope.

The environments around T Tauri-type Pre-Main-Sequence stars have been studied by Gullbring and Gahm (1996) using polarimetric techniques (Turpol) at the NOT. The temporal variations of linear polarization indicate changes in the density and geometry of the scattering circumstellar material, and the wavelength dependence of the polarization is a good indicator of the size distribution of the dust grains.

In the vicinity of hot stars the free electrons in extended circumstellar envelopes can be a significant source of scattering opacity, and give rise to measurable polarization. In particular, the mass transfer in interacting binaries results in accretion streams and disks, which can be studied by polarimetry (e.g. Egonsson and Hakala 1991; Scaltriti et al. 1993), with the help of changing aspect angles due to the binary motion, and possible eclipses of the scattering material.

Good S/N ratio is needed for analyzing polarization variability patterns as a function of the binary orbital phase. The 2.5 m NOT, together with the simultaneous 5-colour Turpol polarimeter, is quite powerful combination for such work, and there are many applications to continue the research in this field at the NOT.

5. Magnetic stars and binaries

5.1. Magnetic braking

New insights to the magnetic braking effects from the interaction of the strong field of highly magnetic white dwarfs with the surrounding medium, have been obtained from circular and linear polarimetry at the NOT. In contrast to the magnetic white dwarfs with rotation periods of a few hours, there are several objects which do not seem to rotate at all. The efficient magnetic braking has stopped their rotation. High precision polarimetry at the NOT with Turpol, compared with earlier published data, has revealed a clear change in the position angle of linear polarization for one of these "non-rotating" white dwarfs, implying a rotation period of about 200 years (Berdyugin and Piirola 1999).

5.2. Magnetic cataclysmic variables (mCV's)

AM Her type binaries are a subclass of cataclysmic variables where accretion from a low mass secondary star occurs on to a highly magnetic ($B \sim 10^7 - 10^8$ Gauss) white dwarf. The optical continuum is strongly polarized due to cyclotron emission from the mildly relativistic electrons moving in the strong field. The rotation of the white dwarf is synchronized with the binary orbital motion. Deviations from synchronism may be caused by nova explosions of the matter accreted on the WD. Tidal and magnetic effects bring the systems back to syncronism on time scales of a few hundred to few thousand years, as seen from period analysis.

The changing orientation of the magnetic field of the spinning white dwarf, together with the concentration of cyclotron emission into directions perpendicular to the field (cyclotron beaming), can have a dominant effect in the observed light and polarization curves. The beaming effect is lowest at low harmonics and gets stronger toward higher harmonics (shorter wavelengths).

Multicolour polarization data for BY Cam (Fig. 1a) show a strong wavelength dependence. The circular polarization curves change their shape completely from the ultraviolet to the infrared. Both positive (right handed) and negative (left handed) circular polarization is observed. This suggests the presence of two separate emission regions close to magnetic poles of opposite polarity.

The basic features of the polarization and light curves of BY Cam can be explained (see Fig. 1b) with a geometric model having the inclination of the spin axis of the white dwarf, $i \sim 50°$ and two extended emission regions, a strong positive circular

Figure 1. **(a)**: *Simultaneous UBVRI circular polarimetry of BY Cam in 1990 Sep 19/20 at the NOT, plotted against the magnetic phase (white dwarf spin period).* **(b)**: *Circular polarization curves for the harmonics 10-5 from the model. With a 30 MG field the harmonics 10 and 5 correspond roughly to U and I, respectively. See text for the details.*

polarization region at colatitude β=30-45° and a weaker negative circular polarization region at β= 20-40° and with a phase lag of about 0.3.

The model reproduces well also the broadening of the polarization minimum near the phase 0.4 towards shorter wavelengths. This is due to the cyclotron beaming effect, which is more pronounced at higher harmonics, i.e., the emission is concentrated to a narrower fan perpendicular to field lines, and decreases more rapidly for viewing directions away from this plane. The emission intensity is zero along the field lines, and due to the dilution effects by unpolarized radiation sources, the net circular polarization has a minimum at the phase (0.4) when we are looking the system nearly pole-on.

Highly extended emission arcs are probably responsible also for the spin-locked polarization variations found (Piirola et al. 1993) in the asynchronous magnetic CV (Intermediate polar) PQ Gem = RE 0751+18 (P_{spin} =13.9 min, $P_{orb} \sim$ 5.3 h). The circular polarization amplitude is small (±2 % in I) and rough field estimates from the circularly polarized flux spectrum suggest B = 5-10 MG. In this low field the polarized radiation observed in the I-band comes from high cyclotron harmonics $(\omega/\omega_c) > 12$. Consequently, the effect of cyclotron beaming is very strong. The basic features of the light and polarization curves can be reproduced reasonably well with a model consisting of two extended emission regions of opposite polarity.

Detailed studies of the optical counterparts of newly discovered mCV's, such as ROSAT sources, have been an important part of the research carried out successfully at the NOT (e.g. Burwitz et al. 1998; Hakala et al. 1993, 1994; Katajainen et al. 1999a,b; Osborne et al. 1994; Piirola et al., 1993, 1994; Rosen et al., 1993; Singh et al. 1995; Szkody et al. 1995).

Multiwaveband polarization measurements are particularly important for inhomogeneous emission regions, and in cases where two (or more) cyclotron sources contribute simultaneously. As the rate of accretion is not the same in the separated regions, significant differences will appear in the polarized spectra for each emission area, sufficient for distinguishing the individual regions in the data analysis and modelling.

6. Blazars

The strong and highly variable linear polarization of blazars has been explained as being due to synchrotron radiation coming from the central black hole along the jet. The variations, both in the degree and position angle of polarization, are believed to be caused by shocks in the jet. However, with the increasing amount of accurate multiwaveband polarization observations, the standard models have difficulties in explaining all the observed polarization variations.

Intensive monitoring of both short-term, from intranight to night-to-night (see Fig. 2), and long-term (on time scales of months and years) polarization variations in blazars has been carried out at the NOT by a group from Tuorla observatory (Sillanpaa et al. 1991, 1993a,b; Takalo 1991, Takalo et al. 1992a,b, 1993, 1994a,b; Valtaoja et al. 1991, 1993; Pursimo et al., 1999). Unique datasets have been obtained, and this work has made the Tuorla team as the leading group in blazar polarimetry in the world, and remarkable new information has been obtained about the highly energetic and complex phenomena in blazar jets.

Figure 2. *Observed daily variations in frequency dependent linear polarization of the blazar AO 0235+164 (Takalo et al., 1992b). The JD numbers give the last two digits of the Julian Date.*

7. Conclusions

Wide range of different polarization behaviour is seen in various astrophysical objects, ranging from newly born stars, just becoming visible from the contracting cloud which gave the birth to the star, to the most distant and energetic objects known in our Universe. There has been remarkable success in explaining the general features of polarization behaviour, both as a function of time and wavelength, with applied geometrical and physical models.

However, much remains still to be done to provide higher quality data for constraining the models, and to further develop the models in order to explain the variety of observed phenomena. Polarimetric research is an example of work where highly specialized and optimized auxiliary equipment can compensate the moderate size of the telescope, and keep us competitive in the front-line of the research to be carried out.

References

Berdyugin, A., Piirola, V., 1999, A&A , in print

Berdyugin, A., Snare, M.O., Teerikorpi, P., 1995, A&A 294, 568

Berdyugin, A., Teerikorpi, P., 1997, A&A 318, 37.

Burwitz, V., Reinsch, K., Schwope, A., et al., 1998, A&A 331, 262
Egonsson, J., Hakala, P., 1991, A&A 244, L41
Gullbring, E., Gahm, G.F, 1996, A&A 308, 821
Hakala, P.J., Piirola, V., Vilhu, O., et al., 1994, MNRAS 271, L41
Hakala, P.J., Watson, M.G., Vilhu, O., et al., 1993, MNRAS 263, 61
Katajainen, S., et al., 1999a, A&A, to be submitted
Katajainen, S., et al., 1999b, the present volume
Kidger, M.,R., Takalo, L.O., de Diego, J.A., et al., 1993, ApJ 407, L1
Korhonen, T., Piirola, V., Reiz, A., 1984, The ESO Messenger, Dec. 1984
Osborne, J.P., Beardmore, A.P., Wheatley, P., et al., 1994, MNRAS 270, 650
Piirola, V.: 1973, A&A 27, 383
Piirola, V., 1988, in 'Polarized radiation of Circumstellar Origin', eds. G.V. Coyne, et al., Univ. of Arizona Press, p. 735
Piirola, V., 1992, The NOT News No. 5, 6
Piirola, V., Scaltriti, F., Coyne, G.V., 1992, Nature 359, 399
Piirola, V., Scaltriti, F., Coyne, G.V., 1999, the present volume
Piirola, V., Coyne, G.V., Takalo, L., et. al., 1994, A&A 283, 163
Piirola, V., Hakala, P.J., Coyne, G.V., 1993, ApJ 410, L107
Pursimo, T., Smith, P.S., Nilsson, K., et al., 1999, A&A submitted
Rosen, S.R., Mittaz, J.P.D., Hakala, P.J., 1993, MNRAS 264, 171
Scaltriti, F., Piirola, V., Coyne, G.V., et al., 1993, ApJS 102, 343
Sillanpaa, A., Takalo, L.O., Kikuchi, S., et al., 1991, AJ 101, 2017
Sillanpaa, A., Takalo, L.O., Nilsson, K., Kikuchi, S., 1993, Ap&SS 206, 55
Sillanpaa, A., Takalo, L.O., Nilsson, K., Kidger, M., 1993, A&A 254, L33
Singh, K.P., Szkody, P., Barrett, P., et al., 1995, ApJ 453, L95
Skody, P., Silber, A., Hoard, D.W., et al., 1995, ApJ 455, L43
Takalo, L.O., 1991, A&AS 90, 161
Takalo, L.O., 1993, Ap&SS 202, 161
Takalo, L.O., Kidger, M., de Diego, J.A., 1992a, A&A 261, 415
Takalo, L.O., Sillanpaa, A., Nilsson, K., et al., 1992b, A&AS 94, 37
Takalo, L.O., Sillanpaa, A., 1993, Ap&SS 206, 191
Takalo, L.O., Sillanpaa, A., Nilsson, K. 1994, A&AS 107, 494
Takalo, L.O., Sillanpaa, A., Nilsson, K., et al., 1994a, A&AS 107, 494
Takalo, L.O., Sillanpaa, A., Nilsson, K., et al., 1994b, A&AS 94, 37
Valtaoja, L., Karttunen, H., Efimov, Yu., et al., 1993, A&A 278, 371
Valtaoja, L., Karttunen, H., Valtaoja, E., et al., 1993, A&A 273, 392
Valtaoja, L., Sillanpaa, A., Valtaoja, E., et al., 1991, AJ 101, 78
Valtaoja, L., Valtaoja, E., Shakhovskoy, N.M., et al., 1991, AJ 102, 1946