Astronomical Polarimetry: Current Status and Future Directions
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Polarimetry Techniques at Optical and Infrared Wavelengths

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Abstract. The techniques and components used to measure both linear and circular polarization at wavelengths from 0.3 μm to 20 μm are reviewed. Some emphasis is given to the implementation of polarimetry on the latest generation of large-aperture telescopes and some of the difficulties being encountered are addressed.

1. Introduction

Polarimetry has played a very important role in the development of optical and infrared astronomy ever since the 1920s when Lyot observed the scattered and hence polarized sunlight from planetary atmospheres (Lyot 1929). The polarization state of radiation contains a wealth of information on the nature of radiation sources, on the geometrical and velocity relationship between a radiation source, scatterer and observer - often on spatial scales that are unattainable by other techniques, on the chemical and physical properties of dust grains, and for the case where these are aligned, on the direction of the magnetic field as projected on the plane of the sky. As polarized flux is independent of dilution by unpolarized radiation it can be used to determine the spectral index of a source. Even when there are two polarized components, these can be separated provided they have different spectral slopes and a different position angle of polarization. Polarized flux can be used to enhance the contrast between reflection nebulosity and a nearby unpolarized bright source (e.g. the circumstellar shell around a star; Gledhill, these proceedings). For a more complete description of the diagnostic power of polarimetry at infrared wavelengths see Hough & Aitken (2003a), and Aitken (these proceedings).

For many decades polarimeters were constructed as private instruments and it was not until the 1980s that the concept of a common-user or facility polarimeter became relatively common and hence available to the non-specialist. Despite this development, and the huge benefits in virtually all areas of astronomy, polarimetry has rarely been included in the baseline design of either telescopes or instruments, at least for night-time astronomy, and adding polarimeters to existing systems often leads to what should have been unnecessary compromises and perhaps less user-friendly instruments for the non-specialist. This is unfortunate as including polarimetry is usually relatively cheap and should be straightforward.

Ideally a polarimeter should measure the full Stokes vector which is a 4-vector with the following components, all having the dimensions of intensity: I (intensity), Q (the difference in intensities between North-South and East-West linearly polarized components, U (the difference in intensities between linearly polarized components oriented at +45° and -45° from North) and V (the difference in intensities between right and left circularly polarized components). Angles on the sky are measured from North to East, i.e. counter-clockwise, starting from the North. The Stokes vector is the most used descriptor of the polarized state of radiation as it can describe completely polarized, partially polarized and unpolarized radiation, and is easily determined from the signals recorded by most polarimeters. Simultaneous measurement of all 4 components is rarely realized and for night-time astronomy most facility polarimeters have concentrated largely on linear polarization. This is unfortunate as circular polarization is an important diagnostic and should not be ignored (Section 5).

In order to maximise the coverage here of the various techniques and devices used in optical and near-infrared polarimetry the reader is encouraged to refer to the numerous references for relevant diagrams as well as additional information. Some particularly useful texts are Tinbergen (1996), di Serego Alighieri (1997), and Keller (2002). Although now rather old, an excellent description of some basic techniques can be found in Serkowski (1974).

2. Some Basic Principles

Most polarimeters consist of two basic elements, a modulator and an analyser. The modulator periodically switches Q, U or V leaving I constant, and a fixed analyser (polarizer) ensures the detector measures only intensity. The ratio of the modulated signal to the average signal is proportional to usually one of Q/I, U/I, V/I. A polarimeter should be designed so that it is limited only by photon shot noise and is not sensitive to atmospheric effects and system gain effects (this does not take into account any limitations from telescope polarization).

Before the advent of the CCD most (single element) optical detectors, used in astronomy had a very fast frequency response, no read-out noise, and the dark current could be made very low by cooling (e.g. photomultiplier tubes). The high frequency response meant that a large range of modulators could be used.

If the modulation rate is higher than $\sim$1 kHz (for example Photoelastic Modulators, Section 3.1), any atmospheric effects (e.g. seeing, scintillation) are eliminated and a very simple but effective polarimeter can be constructed that consists simply of the modulator, a single beam analyser and fast detector. Note that in this case a dual-beam analyser (e.g. a Wollaston prism) is not needed to obtain accurate polarimetry but including such a device - used with a second detector - provides twice the throughput and the observing time is reduced by a factor of two. Using single-element detectors has the advantage that flat-fielding is not a problem but of course such a (stellar) polarimeter is only efficient for point sources.

The introduction of the CCD, with long integration times (seconds to minutes) to reduce the effects of readout noise, and relatively long readout times, meant that the fast modulating devices were no longer suitable (but see Section 3.3) and most polarimeters employed fixed retardance devices such as crystal waveplates, with modulation achieved by rotating the waveplate to set positions (which rotates the plane of polarization relative to the analyser) and then exposing the detector chip (step and stare) until the pixel wells were sufficiently filled to make readout noise negligible. Of course some polarimeters had used crystal waveplates long before the introduction of array detectors. The slow modulation rates meant that determining a Stokes Parameter (Q, U, or V), each requiring integrations at two positions of the waveplate, was very susceptible to even slight atmospheric changes between the two waveplate positions.

This problem was easily overcome by using a dual-beam polarising prism so that both orthogonal polarisations are imaged simultaneously on the detector (see Tinbergen 1996, page 97, for a description of different prisms). Since the sum of these two states is the total intensity, any changes in atmospheric transparency can be compensated for in the data reduction. With this method two images (spectra) are produced on different areas of the detectors that will have very different sensitivities (this and other imbalances between the two beams are referred to as the 'gain table'). These cannot be calibrated better than a few tenths of a per cent but by reversing the polarization states (e.g. by using a rotated half-wave plate for a second exposure) the effects of the different gains can be eliminated. Combinations of two exposures gives I plus one of Q, U, V: for a half-wave plate, angles of 0° & 45° give I+Q & I-Q, 22.5° & 67.5° give I+U & I-U, and for a quarter-wave plate angles of -45° & +45° give I+V & I-V, with angles measured relative to the analyser axis. Each of these intensity pairs occurs alternately in each beam of the analyser, allowing the effects of the different channel gains to be eliminated. For some typical data reduction procedures see Tinbergen (1996, page 100), Berry & Gledhill (1998), Leyshon (1998), and for the case of images taken through a single polarizer Sparks & Axon (1999).

3. Modulators

There are basically three types of modulator: those that have a fixed retardance and fast axis (e.g. crystal waveplates, polymers), those where the retardance is changed in some controlled way (e.g by applying a stress in the case of photoelastic modulators, and by applying a voltage for nematic liquid crystals, Pockels and Kerr cells), and those where the retardance is fixed but the fast axis can be switched (e.g. ferro-electric liquid crystals by applying a voltage). The following sections cover only the most widely used modulators and for further descriptions of these and other devices see Keller (2002).

A term that is often used, and sometimes mis-used, is that of zero-order retarder. A true zero-order $\lambda/4$ or $\lambda/2$ retarder has a physical thickness equal to $\lambda/4$ or $\lambda/2$ divided by the birefringence of the material. These cannot always be produced, especially in the case of crystal waveplates, as they are very thin and not mechanically robust. Physically thicker, multi-order retarders, which are generally to be avoided, have the same retardance as a zero-order retarder at the design wavelength but the retardance changes much more quickly with wavelength, and is also more sensitive to temperature changes and the angle of incidence of the light. A compound zero-order waveplate has mechanical robustness and a retardance that depends on wavelength in the same way as a true zero-order plate (Section 3.2).

3.1. Electro-optical Devices

Photoelastic Modulators The PEMs were pioneered by James Kemp in the early 1970s (Kemp 1970; Kemp 1981). They have become a standard technique for high sensitivity laboratory instrumentation and are commonly used by solar astronomers. A PEM is a slab of non-birefringent material (e.g. fused silica, calcium fluoride) excited via a piezoelectric transducer at its natural mechanical resonance frequency, c/2l, where c is the sound speed in the material and l is the slab length. The oscillating mechanical stress induces birefringence which varies with time t and position x ($0 \rightarrow l$) as $A\sin(\omega t)\sin(\pi x/l)$, where A is the maximum retardance at a given wavelength and this can be tuned to any wavelength by varying the drive voltage of the device.

Second harmonic detection of linearly polarized light using a single PEM measures just the component polarized at 45° to the PEM axis. Thus to measure linear polarization of unknown position angle, the PEM and analyser have to be rotated by 45°. Alternatively, two PEMs can be used (frequencies f_1 & f_2), axes oriented at 45°, and with the analyser axis at 22.5° away from each PEM axis. The detector signals at f_1 & f_2 are proportional to Q and U but the amplitude of modulation is only 50 % of that for a single PEM.

PEMs are true zero-order retarders, they can be tuned to the desired wavelength and can cover 170 nm - 3.5 μm (fused silica), 130 nm - 8.5 μm (calcium fluoride), 550 nm - 18 μm (zinc selenide) and 1.1 μm - 40 μm (silicon). They modulate at frequencies of tens of kHz, have no moving parts (hence no image movement), and can give a polarization precision of $5\text{x}10^{-6}$ (Stenflo 2003).

In fact polarization sensitivities as high as a few parts in 10^7 were achieved by Kemp et al (1987) for the integrated light of the sun. Hough et al (2003) and Hough & Lucas (2003) describe the development of a classical-style polarimeter, using PEMs, triple-wedge Wollaston prisms, and single element Avalanche Photodiodes, designed to detect the polarization signature of the hot-Jupiter extra-solar planets. Model predictions of the fractional polarization of light scattered by such planets, in the presence of light from the star, are typically a few 10^{-6} (Seager, Whitney, & Sasselov 2000).

Despite their obvious advantages PEMs do have some limitations. They have relatively small useable apertures (typically 20 mm, maximum 45 mm), the modulation efficiency is approximately sinusoidal (and hence lower than a device with square wave modulation), and being tuned devices they have limited wavelength coverage and hence are not suited to spectropolarimetry with wide wavelength coverage. Achromatic PEMs have not been made to date, and the Pancharatnam design (Section 3.2) cannot be used as this method minimizes the overall retardance of each component.

Nematic Liquid Crystals The nematic liquid crystals are sandwiched between electrically conducting fused silica windows spaced a few microns apart, and their birefringence can be changed with applied voltage (typically up to ~20V) with the maximum birefringence when the field is zero and the long axes of the molecules are parallel to the window faces (see Figure 2 of Jochum et al 2003). They act as true zero-order retarders, can operate in the visible and near-infrared, and can have clear apertures of ~40 mm. The modulation frequency is ~50 Hz, too low to eliminate atmospheric effects and hence should be used with dual-beam analysers. They have other disadvantages: (i) a residual retardance of ~30 nm even at high voltages, caused by the inability of crystals at the substrate boundary to rotate freely, although this can be compensated by the addition of a retarder attached to the cell; (ii) the retardance changes by about

-0.4 % per °C, so the crystals have to be maintained at a constant temperature; (iii) achromatic devices cannot be produced using the Pancharatnam design for the same reason as PEMs (see above section).

Ferro-electric Crystals Ferro-electric crystals (FLCs) are so-called as they have a permanent polarization. They have a fixed retardance, that is relatively insensitive to temperature, but the direction of the fast axis can be switched by about 45° (the switching angle is rather temperature sensitive). They respond much more quickly to externally applied fields than nematic liquid crystals, with switching frequencies of a few kHz, fast enough to eliminate atmospheric effects. They are true zero-order retarders but have the disadvantage that they cannot be tuned and an appropriate thickness of crystals has to be used to produce a given retardance at a particular wavelength. Recently it has been possible to build an achromatic modulator based on three non-achromatic FLCs combined according to the Pancharatnam scheme useable from 400 nm to 750 nm (Gisler, Feller, & Gandorfer 2003, and see Section 3.2).

3.2. Crystal Retarders

There are a number of birefringent materials that are suitable for manufacturing retarders, usually referred to as waveplates. Commonly used are: quartz (180 nm - 2.8 μm), magnesium fluoride (150 nm - 6 μm), cadmium sulphide (5 μm - 15 μm), and sulphur-free cadmium selenide (5 μm - 23 μm). Modulation is achieved by rotating the fast axis of the waveplate relative to the analyser. For a half-wave retardance, a mechanical rotation of θ degrees gives a rotation of 2θ in the plane of polarization of the incident radiation. With dual-beam analysers sensitivities of $\sim$1 in 10^4, or better, can be achieved and crystal retarders are the most commonly used modulators in night-time astronomy.

Compound Zero-order Plates True zero-order waveplates are very difficult to manufacture as the very small thickness of the plates, at optical and near-infrared wavelengths, makes them unsuitable for any reasonable aperture. Compound zero-order plates are produced by using two plates, each typically $\sim$0.5 mm thick, with a difference in thickness of the two plates equal to the required retardance. Plates made from magnesium fluoride with clear apertures of $\sim$100 mm can be produced. For the usual case of the plates not being achromatic it is essential that the fast axes of the two plates are orthogonal to each other. If this is not the case, a rotation of position angle can occur with wavelength (Hough & Aitken 2003b). These plates are not true zero-order plates and have the same sensitivity to the incidence angle of light as multiple order plates of the same thickness. However, they do have the same variation of retardance with wavelength as a true zero-order waveplate, which is far less than a multi-order plate.

Achromatic Retarders Achromatic retarders can be made by combining two plates made from materials with different birefringence. These can be designed to have the same retardance at two wavelengths and would generally give good performance at other wavelengths if a combination of positive and negative crystals is used. Unfortunately there are no suitable crystal pairs available for making waveplates, and quartz and magnesium fluoride, both positive crystals, are normally used (Serkowski 1974). Far better achromats were proposed by Pancharatnam (1955) in which three identical retarders are used, the outer plates having parallel fast axes, while the fast axis of the inner plate is rotated by $\sim 60°$.

So-called superachromats can be produced by combining 3 identical crystal achromats in a Pancharatnam design and can be used over a wide wavelength range, typically 300 to 1100 nm, they have very good thermal stability and a moderate angular acceptance angle. All these Pancharatnam achromats have a fast axis whose direction changes with wavelength but is very easily compensated by a simple calibration. The standard half-wave superachromats have a change in retardance of only $\pm 0.005\lambda$ and a variation in angle of the fast axis of $\sim \pm 2°$ between 0.31 and 1.1 μm. Quarter-wave superachromats have larger variations of retardance and fast axis with wavelength, and particular care has to be taken when measuring circular polarization (Section 5).

Superachromats have been designed to be used over even more extended wavelength ranges. For example, the Japanese optical-infrared imager and spectrometer, TRISPEC, (Watanabe et al., 2003) uses a single half-wave retarder between 0.34 and 2.5 μm, with a change of retardance of $\pm 0.02\lambda$, which still give a modulation efficiency at any wavelength of over 99 %, and a variation of fast axis of $\sim \pm 4°$ across the whole wavelength range. The Gemini polarimeter (GPOL) will use similar plates (Hough & Aitken 2003b).

Superachromats with clear apertures as large as $\sim$100 mm can be manufactured from single crystals and the FORS1 polarimeter on the ESO-VLT uses a mosaic of 3x3 plates, each 45x45 mm, with a 3 mm gap (Appenzeller et al., 1998, Seifert et al., 2000). The GPOL waveplates have a 95 mm clear aperture with a transparent annulus to increase the field of view for the on-instrument-wavefront-sensors used on Gemini instruments (Hough & Aitken 2003b).

Near-IR achromats, made from magnesium fluoride and quartz have been used at a number of telescopes (Anglo-Australian Telescope, United Kingdom Infrared Telescope & Subaru), with clear apertures up to 100 mm, and a maximum departure in retardance of only $\pm 0.02\lambda$ for a half-wave retarder. Achromats can be made for the 10 μm atmospheric window using CdS and CdSe with relatively good performance although these do not seem to have been used to date in astronomy.

Some Problems with Waveplates Despite their widespread use, waveplates do have some disadvantages. Rotation of the waveplate can produce image motion (caused by any non-parallelism of the plates) and dust specks can cause spurious modulation. High resolution spectropolarimetry can often show spectral modulation in polarization and position angle, produced by multiple reflections within the plates. With compound zero-order plates, often with an air-gap between the two plates, a beating between two (or more) multiple interferences can be observed. Traditionally the ripple has been removed by identifying the separate Fourier components of the ripple in the Q and U spectra and interpolating through them. Aitken & Hough (2001), showed that the effect can be easily removed in the data taking process by averaging data taken at 0° & 45° and those angles +90° for Q, and similarly for U.

3.3. Other Modulators and Modulation Techniques

Using just one Polarization Element Some instruments have just used a two-beam analyser (e.g. a Wollaston) with the modulation achieved by rotation of the entire instrument (Miller, Robinson, & Goodrich 1988). The major disadvantages with this technique are obtaining sufficiently accurate flat-fielding, which limits accuracy to $\sim$0.3 %, susceptibility to instrument flexure, and, for spectroscopy, rotation of the slit on the sky will lead to different sampling of extended objects. See Ageorges & Moorwood (these proceedings) for the use of Wollaston prisms for infrared polarimetry on the ESO-VLT.

Oliva (1997), Pernechele, Giro, & Fantinel (2003) describe a double Wollaston near the pupil plane to obtain simultaneously 4 images containing information on the polarization at 0°, 45°, 90° and 135° to get I, Q & U in one exposure. The prism is made of 2 pieces glued together along a plane surface that is perpendicular to the crystal axis of one of them and forms a 45° angle with the axis of the other. Some of the advantages and shortcomings of this type of device are discussed by Geyer et al (1996).

Fresnel Rhombs Total internal reflections produce a phase shift (or retardance) and a single reflection can be arranged to produce a retardance of $\lambda/8$. Two reflections therefore provide a retardation of $\lambda/4$ and a half-wave retardation can be achieved with 4 internal reflections. Fresnel rhombs are very good achromats as any change of retardance with wavelength arises only from the change in refractive index. One disadvantage is that Fresnel rhombs have only a small acceptance angle as the retardation depends strongly on the angle of incidence. Also, as two reflections are needed to give even a $\lambda/4$ retardance, the rhombs have long optical path lengths which impacts on throughput, and it is also difficult to avoid stress birefringence in thick rhombs (Bennett 1970), making their use fairly limited. It is proposed, however, that CIRES, a cryogenic infrared echelle spectrograph, being developed by ESO (Moorwood 2003) will use a Fresnel rhomb retarder and Wollaston prism for the polarimetry mode, and ESPaDOnS, a cross-dispersed echelle spectropolarimeter for use on the Canada France Hawaii Telescope, will use rhombs between 370 and 1000 nm (Petit et al., 2004). It is argued that another advantage of rhombs is that, unlike crystal waveplates, they do not produce spectral ripples in the polarization spectra (but see Section 3.2).

Polymer Retarders These consist of a sheet of birefringent polymer material laminated between two glass plates. They can be made with very large clear apertures (up to tens of cm) and can be used between $\sim$400 and $\sim$2500 nm. They are true zero-order retarders and can be made achromatic between 425 and 675 nm using multilayer polymer stacks.

Using Fast Modulators with CCDs When CCD detectors were first introduced attempts were made to use them with relatively fast modulators. Miller et al (1988), considered using the CCD as an intermediate storage device whilst using a Pockels cell modulator. The 3-phase CCD allows images to be shifted in either of two directions by changing the clock phase. Exposure of one polarization state could be made for a second, the image shifted and then the other polarization state exposed on the same part of the CCD, and then shifted on the chip. By shifting the images back for subsequent exposures the process could be repeated until enough signal was acquired. Part of the CCD had to be masked for temporary storage of each image while inactive. Thus two images were formed on the CCD, taken with different polarization states but recorded on the exact same pixels of the CCD, so the non-uniform response of the CCD would cancel. In practice it was found that problems with the charge transfer on the chip made the system very inefficient.

Solar astronomers have developed the technique in the single-beam ZIMPOL polarimeters (Keller 2002) which use the very fast modulating PEMs (Section 3.1). As noted in Section 2, a single beam device avoids non-common path and flat-field problems, and because the modulation rate is so fast for PEMs (compared to the seeing changes) images for the two opposite polarization modes are registered practically simultaneously, and as the two image are obtained with the same image pixels the gain table noise is reduced to very small levels. Thus the measurement is fully differential. Keller (these proceedings) describes the design of a novel array detector C^3Po that would provide high sensitivity and precise differential imaging.

In night time astronomy the technique of charge shuffling on CCD detectors for polarimetric measurements has recently been implemented by Jeremy Bailey with the Taurus instrument at the Anglo-Australian Telescope (see their WEB pages).

4. Analysers

For astronomical polarimeters using slow modulation it is necessary to use dual beam analysers so that both orthogonal states of polarization are detected simultaneoulsy. There are two main types, those that produce a lateral shift in the e-and the o-beams and those that produce an angular diveregence. Calcites have been used in a number of optical spectrographs placed below the spectrograph slit, with a lateral beam displacement which is $\sim$0.1 $\times$ the calcite thickness. A simple calcite has the disadvantage that the two beams have different optical path lengths and therefore a different focus. This can be overcome by using a Savart plate, as in the ISIS spectropolarimeter on the WHT (Tinbergen & Rutten 1992). Calcites cannot be used beyond 2.0 μm because of their large opacity to the o-rays. As these optical elements are placed in a non-collimated beam optical aberrations will normally be introduced but these can be minimised by including some optical power in the analyser.

The most commonly used prism to produce an angular divergence between the e- and o-beams is the Wollaston prism, in which the deviation of the two beams is given by $\delta_{eo} \sim 2\arctan[(\mathrm{N}-1)(\mathrm{n}_e-\mathrm{n}_o)\tan\theta]$, where θ is the prism angle, (n_e-n_o) is the material birefringence, and N is the number of prism wedges. One of the major problems is the lateral chromatism arising from the wavelength dependence of birefringence, producing elongated images in the polarization dispersion direction when using wide band filters (note that some prisms, e.g. the Foster prism, have an angular separation which is wavelength independent). Materials with relatively low lateral chromatism also tend to have low birefringence giving a small separation of the two beams, requiring a focal plane mask with relatively small slots. Although there are some materials with both high birefringence and low lateral chromatism, such as Lithium Yttrium Fluoride (Oliva et al 1997) and α-Barium Borate, they are extremely difficult to obtain in sufficient quantity to produce a Wollaston prism, and the easily available magnesium fluoride is the most widely used material (see Hough & Aitken 2003b for a description of a number of prism materials).

Two beam prisms have been used at optical wavelengths since the start of astronomical polarimetry but they were not introduced in the infrared, where the prisms need to be cooled, until 1993 (Hough, Chrysostomou, & Bailey 1994). An additional problem in the infrared is being able to cement the prism sections together and normally a soft cement is used to allow for differential contraction and expansion (the crystal thermal expansion coefficients are different along orthogonal axes). Magnesium fluoride, lithium niobate and β-barium borate prisms have been used successfully in the near-infrared (note that the latter has an absorption at the long wavelength end of the K-band). At mid-infrared wavelengths single beam analysers, normally wiregrid polarizers, have been used to date, although Packham (in these proceedings) describes a cadmium selenide Wollaston to be used with CanariCam, a mid-infrared imager and spectrometer being constructed for the Spanish GranTeCan telescope. The lack of suitable cements requires the use of an air-gap prism which limits the range of prism angles that can be used and the design of the AR coatings for the slant faces is difficult.

5. Circular Polarimetry

One of the reasons circular polarimetry is less commonly used by night-time astronomers is that the degrees of polarization are generally small, although there are exceptions such as the AM Her binaries (Warner 1995), and for some star-forming regions (Chrysostomou et al., 2000). Additionally, false circular polarization signals can occur in the presence of a large linear polarization, unless the polarimeter is appropriately designed. The lack of use has led Jaap Tinbergen (2003) to comment that "measurement of circular polarization is mostly looked upon as a specialist craft, applied by polarization freaks to answer uninteresting questions". As Tinbergen notes, however, circular polarimetry is a very important diagnostic of many processes in astrophysics (see also Hough & Aitken 2003a) and it should be made more available at Observatories.

In principle the technique is the same as for measuring Q and U, except a quarter-wave retarder is used with its optic axis at $\pm 45°$ relative to the analyser axis. However I, Q, U are often much larger than V and cross-talk from the stronger signals can be a problem. The measurement of linear as circular polarization arises from the retardance not being a quarter-wave and/or the fast axis of the retarder not being at precisely $\pm 45°$ relative to the analyser axis. The latter is usually a more serious problem and arises either through mechanical misalignment and/or the variation of the fast axis with wavelength which occurs with all the Pancharatnam achromats (Section 3.2). For example, in the presence of 100 % linear polarisation in the U Stokes vector, a $0.1°$ offset in the zero-degree position leads to a $\sim$0.2 % circular polarisation, a $0.2°$ offset to $\sim$0.3 % circular, and a $1°$ offset to $\sim$1.7 % circular. The cross-talk is proportional to the degree of linear polarisation (Hough & Aitken 2003b).

One of the easiest methods of eliminating the problem is to rotate a half-wave retarder in front of the stepped quarter-wave plate, but is often not included through lack of space. Billings (1951) gives the time averaged ratio of transmitted linear to incident linear polarization as $\epsilon^2/4$ for a retardance of $\pi+\epsilon$, with $\epsilon \ll 1$. For a superachromat (Section 3.2), ϵ is typically 2°, giving a ratio of ∼3000, and Chrysostomou et al (2000) report obtaining linear depolarization ratios of ∼2000. Another technique is to take measurements with the polarimeter rotated through 90°, reversing the sign of the cross-talk circular polarization, but is inconvenient for extended sources when a polarization mask is used.

6. Polarimeters as Differential Imagers

One of the major contemporary science drivers is the imaging of faint objects close to a bright star, such as circumstellar disks and extrasolar planets. The main limitation in imaging a faint object close to a very bright star is the speckle halo from the central bright source. Speckle noise can be reduced by differential imaging, that is splitting the light into two beams and taking the difference with the assumption that the speckles are the same in the two images. Differential multiwavelength observations have been suggested to minimize such noise, although this approach is limited by the chromaticity of the residual noise and hence narrow band filters that are close in wavelength have to be used with the planet (say) relatively much brighter in one of the filter bands. An alternative approach is to use the inherent differential nature of dual-beam polarimetry as the atmospherically scattered speckle patterns are indistinguishable in the two orthogonal polarizations. Thus the difference image constructed from orthogonal polarizations removes the scattered light, leaving eventually a polarized brightness image of the planet or circumstellar disk. A high polarization accuracy is still needed as the brightness of the planet or disk is much lower than the atmospheric speckle halo of the central star. Useful papers are: Kuhn, Potter, & Parise (2001), Kuhn (these proceedings), Apai et al (2004) & Schmid et al (these proceedings).

7. The Future of Polarimetry on the Large Telescopes

Despite the new large aperture telescopes being ideally suited to the requirement of large photon numbers for accurate polarimetry, there are increasing difficulties in providing facility polarimeters. A basic problem is that the modulator should be the first element in the optical train, which means using the unfolded Cassegrain focus. Large focal planes and the use of fast telescope beams requires large modulators which are extremely expensive, assuming they can be manufactured in the first place. The problem is compounded by the increasing use of adaptive optics that requires several reflections and drives the modulator to be some distance away from the instrument (adaptive secondaries would avoid this problem), and there are additional difficulties for polarimetry with optical and infrared interferometers (Quirrenbach, these proceedings). Of course, high spatial resolution is very important as polarization is a vector quantity and can be easily reduced in magnitude when not spatially resolved.

Even without AO many of the large telescopes make increasing use of the Nasmyth focus for the very large instruments and it is virtually impossible to have a modulator placed before the Nasmyth mirror. All these difficulties are likely to make more and more polarimetry having to be carried out after an oblique reflection. This will require more careful calibration as a reflection will introduce linear polarization in an unpolarized beam and can also convert linear to circular or elliptical polarization, effectively depolarizing the beam (Stuick et al., 2004). Situations where this is not a major problem are (i) highly polarized reflection nebulae where the overall polarization pattern is more important than the absolute degrees of polarization (Potter 2004) and (ii) velocity resolved spectropolarimetry where the instrumental polarization will not vary across spectral features.

Despite some of these difficulties polarimetry remains one of the key diagnostics available to astronomers on future generations of telescopes.

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Discussion

Wolstencroft: In the 1970's Jim Kemp and I looked at the potential of using the beat frequency approach (combining 2 PEM's) to make the effective modulation frequency compatible with an array detector. This did not work for the mid-IR (ZnSe), but we felt it could in fact be used in the optical. What is your opinion?

Hough: I don't know how stable the beat frequency would be and I believe you would still need to use some charge shuffling on the chip. There could be significant advantages, however, if the number of transfers were considerably reduced, matching the much lower beat frequency.

Bagnulo: Observations of the circular polarization of spectral lines are a fundamental tool for detection of stellar magnetic fields. Cross-talk is of no concern because linear polarization from magnetic field is a second order effect compared to circular polarization.

Hough: Circular polarization (CP) has been very much overlooked as an important diagnostic in astronomy. Although multiple scattering usually generates low degrees of CP it does give information on scatters other then the last one, and scattering off aligned grains can give very high degrees of CP. In both cases, the properties of dust grains are far better constrained from a combiation of LP and CP. Even when very high linear polarization is present, low degrees of CP can be measured accurately provided the polarimeter design or method of acquiring data are appropriately considered.