Cosmic Magnetic Fields:
From Planets, to Stars and Galaxies
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Imaging polarimetry as a diagnostic tool

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Abstract. Some of the earliest polarimetric measurements made in astronomy were concerned with the polarization of the interstellar medium resulting from dust grains aligned in the Galactic magnetic field. More than 50 years later, polarimetry continues to be an important diagnostic of field structure on size scales ranging from planetary to galactic. The use of both linear and circular polarimetry at optical and infrared wavelengths can provide additional insights into the nature of dust particles, their alignment in magnetic fields and the field topology. Given the science benefits that polarimetry offers it is perhaps surprising that the continued existence of polarimetric facilities on current and next generation large telescopes needs to be ensured.

Keywords. Magnetic fields – polarization – scattering – instrumentation: polarimeters

1. Introduction

Polarization is a natural tracer of asymmetry, and the interaction between light and matter in many astrophysical environments is inherently asymmetric. Often, the presence of a magnetic field imparts the necessary asymmetry, an example being electrons spiralling around field lines and emitting polarized synchrotron radiation. Even where the emission is unpolarized at source, subsequent interactions often produce polarization before the light reaches Earth; scattering of starlight by dust grains in circumstellar environments can produce high degrees of linear (and sometimes circular) polarization at optical and infrared wavelengths; extinction by elongated and aligned dust grains in the ISM can induce polarization up to a few per cent at optical wavelengths; thermal emission from dust in star-forming regions results in polarization from the mid-infrared through to the sub-millimetre; radio emission from extragalactic sources is polarized due to Faraday rotation in our Galaxy. Even the CMB radiation pervading the entire Universe is polarized. Indeed, it is hard to think of an astronomical source that is not polarized to some degree at some wavelength. It may seem surprising then that this polarimetric information is often discarded and that many instrument and telescope systems which are insensitive to polarization continue to be built.

This review will concentrate on polarization produced by dust, principally at optical and infrared wavelengths; polarization due to the Zeeman effect, Faraday rotation and synchrotron emission are reviewed elsewhere in these proceedings. The technique of imaging polarimetry in particular will be described, along with its history and applications. For typical astrophysical dust grain sizes ($\sim 10^{-1}$ μm), at wavelengths less than 5 μm, polarization due to scattering usually dominates, especially in optically thin environments. However, if the optical depth is significant, then dichroic polarization can be important if the grains are aligned. At wavelengths greater than 5 μm, where the scattering cross-section for sub-micron grains becomes negligible, any polarization must come from dichroic absorption and emission of radiation from aligned grains. Emissive polarization is particularly important in the mid- and far-IR.

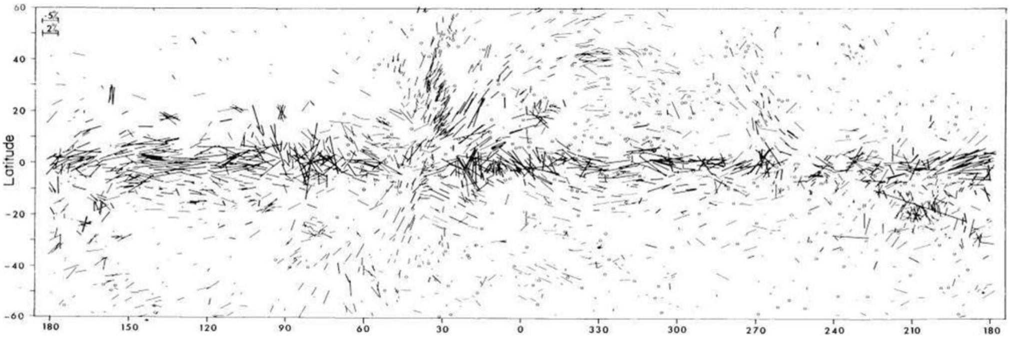

Figure 1. Optical polarization vectors for ∼ 7000 stars, indicating the projected Galactic magnetic field orientation. From Mathewson & Ford (1970).

Polarimetry provides an important tool for investigating the structure of magnetic fields. Aligned dust grains seem to be present in many astrophysical environments. Although the details of the alignment process may not be known exactly, grains with rotational frequencies of 10^5-10^6 Hz develop a magnetic moment due to the Barnett effect (Aitken *et al.* 2004; Hough & Aitken 2003) so that their spin axes precess around the B-field giving a net polarization. Where grains do have a preferential alignment over the resolution element of the observation and where that alignment is reasonably coherent along a line-of-sight, then a net linear polarization (LP) can be observed due to dichroic extinction or emission, depending on the wavelength/grain-size and optical depth. If the alignment orientation changes along a line-of-sight, due to structure in the magnetic field for example, then LP can be converted to circular polarization (CP), and vice versa due to the circular birefringence of the medium. Scattering from aligned grains can produce degrees of CP in the region of tens of per cent, much larger than those produced by birefringence. In addition to being an excellent diagnostic of grain alignment and magnetic fields, polarimetry can also be used to place limits on grain properties, such as the size distribution, shapes, compositions and structures. This is especially the case where observations are obtained at several wavelengths and information on the chemical composition of the dust is available, for example from spectroscopy of its emission features or from a general knowledge of the environmental chemistry.

2. Early polarimetric work

The link between polarimetry and magnetic fields is illustrated by the fact that some of the earliest astronomical polarimetric measurements of stars were used to infer the large-scale structure of the Galactic magnetic field. These observations used photoelectric photometers with polaroid sheets as analysers. Typically the instrument as a whole was rotated through various angles to recover the polarimetric information (Hiltner 1949; Hall & Mikesell 1949). Hiltner (1949) observed stars in the Perseus cluster, noted the tendency for the polarization E-vector to lie parallel to the Galactic plane and speculated that this could be related to a large scale Galactic magnetic field, which would require the dust grains to be both elongated and aligned. Hiltner (1951) measured the polarization of 841 stars and arrived at the same conclusions. This was all put onto a firmer theoretical footing by the publication in 1951 of Davis & Greenstein's famous paper explaining how spinning dust grains could align in the presence of a magnetic field due to the torque induced by paramagnetic relaxation (Davis & Greenstein 1951).

The first optical polarization survey was published by Mathewson & Ford (1970) and combined a southern hemisphere survey of 1800 stars observed at Siding Springs, with

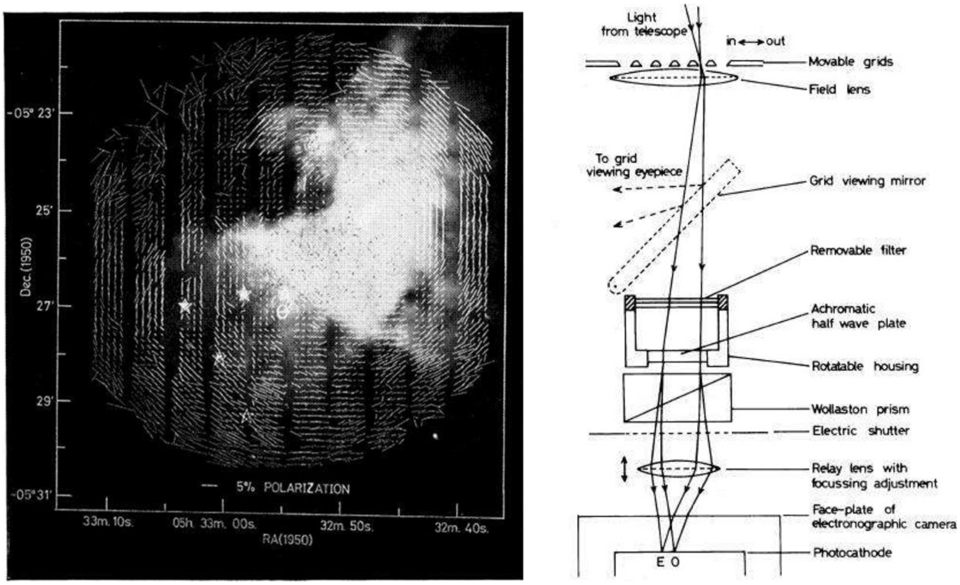

Figure 2. a) Imaging polarimetry of the Orion Nebula region by Pallister *et al.* (1977) showing an 8 arcmin square region. The scattering pattern indicates that much of the region is illuminated by sources in the central Trapezium Cluster, principally Θ_1 and Θ_2 Orionis. b) A schematic illustration of a two-channel polarimeter design, from Scarrott *et al.* (1983)

the northern hemisphere observations of Hiltner, Hall and others. This resulted in maps of the projected Galactic B-field (Fig. 1) at various distance intervals, showing agreement with radio observations and providing evidence for kpc-scale fields.

3. Imaging polarimetry

Before the mid-1970s, polarimeters were effectively single-pixel devices, summing intensities over an aperture. Imaging of a sort could be carried out by repeatedly stepping the aperture on the sky (e.g. Fig. 1) but this is time consuming and limited by the accuracy with which apertures can be reliably positioned. Bingham *et al.* (1976) published one of the first imaging polarimetric observations, of the galaxy M82, shortly followed by observations of M104 (Scarrott *et al.* 1977) and M42 (Pallister *et al.* 1977), shown in Fig. 2a. These optical wavelength results used a two-channel imaging polarimeter incorporating a rotating half-waveplate to rotate the plane of polarization of the incident light, and a Wollaston prism to separate orthogonal polarisation states (Fig. 2b). This system, which has now become a standard configuration, had already been used by Öhman (1939) to measure the polarization of the Moon and comets, and originally dates back to Pickering (1886) who used his 'polarigraph' to measure atmospheric polarization.

Apart from efficiency considerations, an important advantage of imaging polarimetry is that it allows polarization to be measured on a spatial scale determined by the seeing-limited resolution of the telescope. This is necessary in order to recover complex structure, for example in scattering patterns around protostars or in the detailed structure of a magnetic field. As polarization is a vector quantity, poor spatial resolution may result in a decreased polarimetric signal; an extreme example would be the summation of a centrosymmetric polarization pattern to a net polarization of zero in an aperture centred on the source.

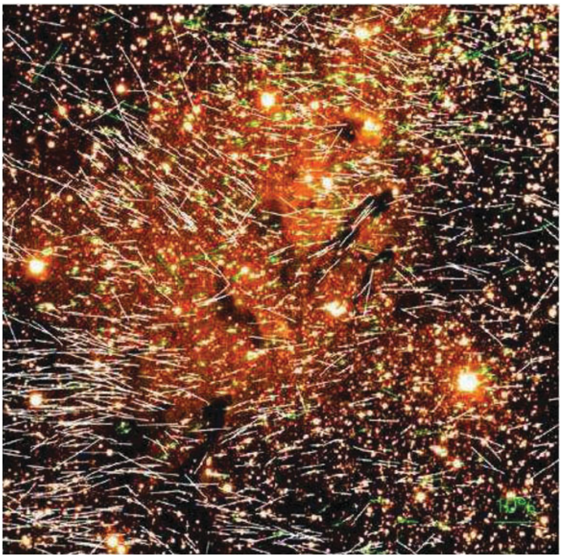

Figure 3. A H-band image of the Eagle Nebula (M16) overplotted with stellar polarizations indicating the presence of dust grains aligned in an ordered magnetic field. From Sugitani *et al.* (2008).

CCD detectors began to be used regularly for optical polarimetry from the early 1980s (e.g. Scarrott *et al.* 1983) and advances in infrared detector technology also allowed imaging polarimetry up to 5 um using InSb arrays. The first common-user infrared camera was IRCAM, commissioned on the UK Infrared Telescope in 1986 (McClean *et al.* 1986), which was later fitted with a Wollaston prism and waveplate system in 1995 to allow imaging and spectropolarimetry between 1 and 5 μm. Although perhaps of less interest to European astronomers, a near-infrared polarimetry module is also planned for the 6.5-m MMT telescope in Arizona (Packham & Jones 2008). MMT-POL will use a Wollaston prism and take advantage of the MMT's adaptive secondary, providing AO correction with no off-axis reflections, to perform high-precision imaging polarimetry between 1 and 5 μm. Despite the relative maturity of the technique, imaging polarimetry continues to be under-used, which must be at least in part due to the scarcity of common-user facilities, especially on the 8-m class telescopes.

4. Exploring magnetic fields with imaging linear polarimetry

There are many applications in which polarimetry provides a novel approach to a particular observational problem. Examples are its use as a differential imaging technique for the detection of faint objects around bright stars (particularly circumstellar discs, debris discs and, ultimately, exoplanets), and its use to probe hidden sources, such as embedded protostars or the nuclei of AGN. In this section, we briefly highlight some examples of the use of linear polarimetry in the detection and investigation of magnetic fields.

4.1. *Polarimetric surveys*

For a number of years, large format CCDs have been used at optical and near-infrared wavelengths for major imaging surveys. Ongoing surveys include the UKIRT Infrared Deep Sky Survey (UKIDSS; www.ukidss.org) in the J, H and K bands, and in 2009 the dedicated survey telescopes VISTA (www.vista.ac.uk) and VST (www.eso.org/sci/) are due to begin operation. However these facilities do not include polarimetry. A linear and circular polarimetry survey of the southern sky is being undertaken using the Japanese Infrared Survey Facility (IRSF)†, a 1.4-m telescope, located at the SAAO in South Africa. The sky can look very different in polarized light, revealing a wealth of information not visible in direct images, such as diffuse reflection nebulae, circumstellar discs and, by their lack of polarization, regions dominated by intrinsic emission lines. In addition, the large number of point sources available in a wide-field image can be investigated using simulated aperture polarimetry to look for unresolved circumstellar discs or to study the foreground polarization due to dichroic absorption by dust grains aligned in a magnetic field. The SIRIUS camera attached to the IRSF telescope has three HgCdTe Hawaii arrays allowing simultaneous J-, H- and K-band imaging using dichroics, and is equipped with a single channel (wire-grid) polarimeter (SIRPOL; Kandori *et al.* 2006). The image shown in Fig. 3 is from Sugitani *et al.* (2008) and shows a H-band polarization map of point sources in an 8×8 arcmin region of the Eagle Nebula (M16). M16 is a star-forming region, with numerous very young objects, and is famous for the gas and dust pillars seen with HST. The polarization vectors appear to be well aligned, suggesting an ordered large-scale magnetic field, with the dominant field direction at position angle 80-90 deg.

4.2. *Mid-infrared imaging polarimetry*

The arrival of mid-infrared arrays made imaging polarimetry possible from the ground in the 10 and 20 μm (N and Q) bands, allowing polarized absorption and thermal emission from magnetically aligned dust grains to be detected. A dedicated N-band mid-infrared polarimeter, NIMPOL, is described by Smith *et al.* (1997) and is based on a single-channel design with a rotating CdS half-waveplate and a fixed cold wire-grid analyser. The instrument has been used to map magnetic field structure at arcsecond resolution in the Galactic Centre (Aitken *et al.* 1998), in the Orion star-forming region (Aitken *et al.* 1997), and in individual objects such as the massive evolved star η Carinae (Aitken *et al.* 1995). See Hough & Aitken (2003) for a review of infrared polarimetry.

Using NIMPOL on the UK Infrared Telescope, Aitken *et al.* (1998) mapped the magnetic field structure in the SgrA* region of the Galactic centre at 12.5 μm. They noted that the field direction followed the northern arm and appeared unperturbed even in the region of embedded OB stars and clusters, suggesting a field strength of at least 2 mG in the vicinity of IRS1. The polarimetry was used to construct a 3-D representation of the field topology.

Common-user facilities capable of imaging polarimetry in the mid-infrared are rare, one example being Michelle, on Gemini-North. There is currently no equivalent polarimetric facility on VLT although CanariCam should be operational on the 10.4-m GranTeCan telescope on La Palma in 2009. CanariCam will be unique in being the first dual-channel mid-infrared polarimeter, incorporating a large CdSe Wollaston prism, offering much-improved efficiency over previous single-channel designs (Packham, Hough & Telesco 2005). At wavelengths longer than 20 μm, the use of polarizing prisms becomes problematic. A possible novel solution to this issue is the use of a polarization grating as a two-channel analyser, a concept that is being explored for a proposed mid-infrared polarimeter for SOFIA (Packham *et al.* 2008). This instrument would function between 5 and 40 μm. The ability of SOFIA to extend the wavelength coverage beyond that available from the ground is particularly important when we realise than none of the current

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† http://www.z.phys.nagoya-u.ac.jp/~irsf/index_e.html

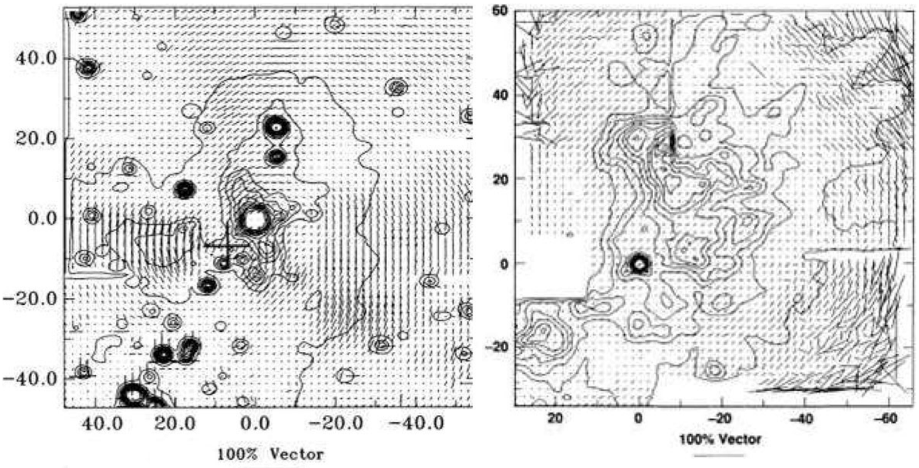

Figure 4. *Left:* A K-band image and polarization map from Minchin *et al.* (1991) showing continuum emission from IRc2, scattered in the surrounding dust cloud. *Right:* Imaging polarimetry in the narrow-band light of H_2 shows the signature of the magnetic field threading the dust sheet in front of the IRc2 outflow. From Chrysostomou *et al.* (1994).

and planned infrared space missions (e.g. Spitzer, JWST, Herschel) will have polarimetric options.

4.3. H_2 *imaging polarimetry*

A standard method for investigating the polarizing properties of a dust cloud is to image the polarization of background light that has passed through the cloud. Where a diffuse unpolarized background source is available, then imaging polarimetry allows the magnetic field in the cloud to be mapped. The main body of the OMC-1 molecular cloud in Orion is illuminated by IRc2, a higly embedded protostar, which appears to be powering a bipolar outflow. CO mapping shows the blue and red-shifted components of the high-velocity outflow, which is interacting with the surrounding molecular material creating shocks. The shocked H_2 1-0 S(1) emission is unpolarized and can be used to probe the structure of the overlying magnetic field (Chrysostomou *et al.* 1994). Broad-band imaging polarimetry in the near-IR continuum (e.g. K-band, see Fig. 4 *left*) shows a reflection nebula (resulting from scattered light) illuminated principally by IRc2 (Minchin *et al.* 1991). However, narrow band Fabry-Perot imaging polarimetry of the H_2 line shows polarization consistent with dichroic extinction in a foreground medium of magnetically aligned grains and so traces out the morphology of the field (Fig. 4 *right*). The field is roughly aligned with the outflow axis, although there is evidence for a twist in the region of IRc2 (also see Aitken, Hough & Chrysostomou 2006).

5. Imaging circular polarimetry

Polarization, especially determined as a function of wavelength, can be used to derive properties of the dust particles such as their composition, size, shape and degree of alignment. This is especially the case if the CP is measured as well as the LP. However, circular polarimetry is a less commonly used technique than linear polarimetry, and again this is to some extent dictated by the available facilities. In the optical, CP can be measured using ISIS on WHT and FORS on VLT. In the infrared, the UIST imager/spectrometer on UKIRT can be used.

In general, in the presence of magnetic fields, and hence aligned grains, we need to consider a full Stokes radiation transport solution including differential extinction (dichroism) and birefringence as well as scattering. Although multiple scattering from non-aligned grains (i.e. spherical or randomly oriented) can produce CP, it is inefficient and results usually in less than 1 per cent polarization. These low polarizations have been observed in a number of pre-main sequence objects in the near-infrared, such as the Chamaeleon Infrared Nebula (Gledhill, Chrysostomou & Hough 1996) and GSS30 (Chrysostomou *et al.* 1997). These objects are often linearly polarized at several tens of per cent, so care must be taken to ensure that CP is not erroneously measured, due to 'cross-talk' (conversion of LP to CP) in the polarimeter. This can occur if the retardance of the quarter-waveplate is not exactly quarter-wave for the input wavelength, or if the fast axis of the quarter-waveplate is not aligned ±45 degrees with the analyser axis (e.g. Hough & Aitken 2002). In the ISIS and UKIRT circular polarimeters, this is achieved by continuously rotating a half-waveplate up-stream of the polarimeter, to average the incident LP to close to zero.

Large degrees of both LP and CP can be produced in the presence of aligned grains. Consider the study of Whitney & Wolff (2002) where they take a simple spherical nebula with a uniform density of oblate spheroids with axis ratios of 2:1. The spheroidal grains are aligned with their symmetry axes along the vertical axis of the nebula, corresponding to a magnetic field along this same axis. They find that these aligned grains can produce $\pm 25 - 40$ per cent CP, whereas non-aligned grains would produce a maximum CP of less that 1 per cent. This suggests that, in environments where light propagates through regions of aligned dust grains, especially along optically thick paths, then CP produced by scattering and dichroism can be an important diagnostic of the field.

5.1. *Circular polarization from aligned grains*

Degrees of CP of up to 17 per cent in the K-band were reported in the OMC-1 region in Orion by Chrysostomou *et al.* (2000), and to date this is the highest degree of CP seen in diffuse nebulosity. Also see Buschermohle *et al.* (2005) for a wide-field CP survey of the OMC-1 region. Chrysostomou *et al.* (2000) found that high CP occurred in regions where high LP was also seen (although the reverse was not the case) and speculated that the CP resulted from the scattering of infrared light, originating from IRc2, by dust grains aligned in a structured magnetic field within the OMC-1 cloud. A simple model was proposed to show that the required degrees of CP could indeed be produced with the proposed field geometry. More detailed modelling by Lucas *et al.* (2005) was able to reproduce both the CP and LP in the region, as well as placing constraints on the field configuration and grain axis ratio, concluding that the CP results primarily from dichroic extinction.

5.2. *Circular polarization and helical field structure*

Magnetic fields have been thought for many years to play a crucial role in regulating accretion onto protostars, both in powering and shaping outflows and removing angular momentum from disc material, to allow the protostar to gain mass. Getting evidence for the morphology of these fields has been tricky though – and this is an area in which polarimetry can help. In particular, CP can provide evidence for changing grain/field alignment directions along the line-of-sight and hence the presence of twisting fields.

The HH135/136 outflow is associated with a young stellar object (YSO), thought to be an intermediate mass Herbig Ae/Be star, in the Carina nebula at a distance of approx. 2.7 kpc. Fig. 4 shows total intensity (I) and fractional circular polarization (V/I) in the H- and K-bands (Chrysostomou, Lucas & Hough 2007). The peak polarization in the top

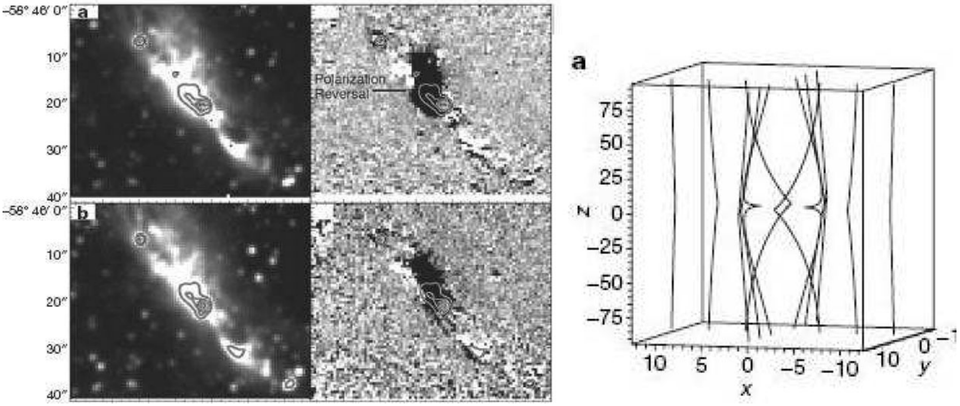

Figure 5. *Left:* K-band (upper) and H-band (lower) images of the HH135/136 outflow, with intensity (I) on the left and fractional CP (V/I) on the right. The CP peaks at −8 per cent (black) in the K-band and −3 per cent (black) in the H-band. *Right:* Helical field models used to reproduce the observed CP data. From Chrysostomou, Lucas & Hough (2007).

K-band image is −8 percent (black) and −3 per cent in the lower H-band image. This is intermediate between the low (less than 1 percent) CP seen in a number of low mass YSO outflows (e.g. ChaIRN, see above), which can be produced by multiple scattering from non-aligned particles, and the higher polarizations of 17 per cent seen in the high-mass star-forming region of Orion, which have been attributed to a combination of scattering and dichroic extinction by aligned grains. This makes sense if we assume that stronger magnetic fields (and hence more efficient grain alignment) tend to be associated with higher-mass star formation.

In HH135/136, the north-east lobe is mostly negatively polarized and the south-west lobe mostly positively polarized, and the sign of CP flips between quadrants. However, the sign flipping occurs on the limb, rather than on the axis. The latter is expected for an axial aligning field (as shown in the models of Whitney & Wolff 2002). The degree and pattern of CP and also LP, which is closely centrosymmetric, have been modelled using a pinched and twisted field morphology as shown on the right in Fig. 4 (Chrysostomou, Lucas & Hough 2007; also see Lucas *et al.* (2005)). The majority of CP produced in this model comes from dichroic extinction.

6. Summary

Astronomical polarimetry has a long history and has contributed enormously to our understanding of many astrophysical processes, particularly where a magnetic field introduces an asymmetry, such as the alignment of elongated dust particles. Once a niche area undertaken only by aficionados with their own private instruments, polarimetry is now a common-user activity. This has resulted not just from an appreciation of the power of the technique, but also from the availability of reliable instrumentation and pipelining software that removes the need for detailed specialist understanding of the technical details. Imaging polarimetry in particular has come of age and should benefit enormously from the increased spatial resolution and light-gathering power of the next generation of large telescopes. However, the continued availability of polarimetric facilities on future large telescopes is in some doubt. The standard location for a polarimeter has always been the Cassegrain focus, where instrumental polarization can be minimised by avoiding off-axis reflections (see Hough 2007). Cassegrain focci are now less common on 8-m and larger telescopes and future instruments are likely to be so large that they must necessarily be located at a Nasmyth focal platform or at a gravitationally invariant focus. This immediately means that a significant, and often time-variable, systemic polarization is introduced by the off-axis reflection at the M3 mirror. At the VLT, for example, the infrared instrument NACO provides AO-corrected imaging polarimetry in the H- and K-bands, but the modulator and analyser are located within the instrument, after the M3 reflection. This results in 'instrumental' polarization of several per cent, which is at the level of the intrinsic polarization of many astronomical sources, so that accurate calibration is required if a meaningful detection can be realised. Detection of polarization much below 1 per cent is difficult with such a system.

Some progress can be made by the use of compensating mirrors and optics, which act to cancel the telescope polarization (e.g. see Tinbergen 2007). The next generation of larger telescopes are likely to be even less polarimeter-friendly. The current concept for the E-ELT, for example, involves 5 mirrors, three of which are off-axis. In addition, the adaptive nature of the mirrors, required to achieve the best image quality possible with a 42-m primary, means that the induced polarization of the telescope system is likely to be very difficult to characterise and compensate for.

In the case of space-based observatories, there is an obvious imperative to keep mechanical systems as simple and trouble-free as possible; repairing a malfunction due to a stuck modulator may be impossible and may jeopardise the whole instrument. However, both ISO and HST implemented polarimetric facilities. In particular HST has seen impressive results with many programs benefiting from polarimetry in the optical and near-infrared. Amongst the recent and near-future infrared space missions though, there is no polarimetry. With a properly designed polarimeter, then polarimetry can be achieved effectively from the ground, as long as the desired wavelength is in a region of atmospheric transmission. This makes it all the more important to include polarimetric facilities on future ground-based telescopes.

Acknowledgements

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Discussion

KOUTCHMY: Could you comment on the observations of neutral points (singularities on the polarization map where the polarization reaches a zero value like it is in the case of the Crab Nebula) with patterns like 'focus', 'saddle' etc

GLEDHILL: Neutral points and other effects often result due to an averaging effect when a lack of spatial resolution, for example due to seeing, causes the Stokes intensities to sum close to zero. Alternatively a neutral point could result if the aligning field is tangled on the scale of the measurement.

ZINNECKER: This was a wonderful summary of polarimetric techniques and results. I hope the forthcoming extremely large telescopes (ELTs) will be equipped with polarimetric capabilities, given the strong community interest in magnetic field science. I think ESO is considering polarimetric instrumentation for the E-ELT, but what about the Americans for their TMT?

GLEDHILL: Indeed, I hope polarimetry goes ahead on E-ELT, but it will be challenging given the number of off-axis reflections before the first usable focus in the planned design. I haven't heard of any polarimetry plans for TMT