

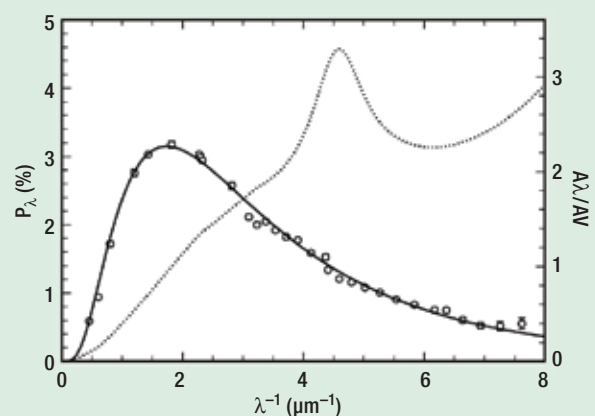
Polarimetry: a powerful diagnostic tool in astronomy

James Hough describes the importance of polarimetry to astronomers – and the need to ensure that this key tool remains available at future telescopes.

ABSTRACT

Knowledge of the polarization state of radiation provides far more astrophysical information than intensity alone. Polarimetry has played a key role in the development of modern astronomy, providing insight into physical processes occurring in systems that range from our own solar system to high-redshift galaxies. The focus of this article is on the many opportunities polarimetry presents to virtually all areas of astronomy.

1: Comparison of the interstellar linear polarization and extinction along the line of sight to the reddened star HD 99872. The points plot the observed polarization, and an empirical fit based on the Serkowski formula with $\lambda_{\text{max}} = 0.58 \mu\text{m}$ (continuous curve) is also shown. The extinction (dotted curve) is represented by a fit to observational data. The figure is taken from Whittet (2004) who references the data sources.



At some level, all sources of radiation, whether in the laboratory or in the sky, are polarized; indeed, a completely unpolarized source is probably unachievable. The polarization is produced in various ways, including directly from some radiation processes (e.g. cyclotron and synchrotron emission), from differential absorption of radiation passing through the interstellar medium, and perhaps most commonly from the scattering of radiation. Fractional polarizations of interest to astronomers range from tenths to, far less frequently, parts per million. Interestingly, one of the most sensitive polarization measurements ever made was by James Kemp in 1987, who showed that the fractional linear polarization of the integrated light from the Sun was less than 2×10^{-7} . The box on p3.32 defines and explains the physical basis of polarization.

Measuring polarization

High-precision polarimetry is far easier than photometry, at least from ground-based telescopes. All polarimeters, whether for imagers or spectrometers, follow the same basic principle, with a polarization *modulator* followed by an *analyser*, converting any polarized component into a light intensity that is measured by the detector. The amount of polarization is essentially the difference in light intensity at two predefined states of the modulator, divided by the total intensity. If the light is unpolarized then the detector sees a constant intensity, regardless of the state of the modulator. There are various modulators such as photoelastic modulators, Pockels cells and liquid

crystals, that can be modulated by the application of a voltage, and crystal waveplates that are mechanically rotated. Analysers are usually in the form of dual-beam polarizing prisms, such as Wollaston prisms, that lead to greater accuracy in measuring polarization by simultaneously imaging both orthogonal polarization states on to the detector, and provide the most efficient use of the incident light. A further benefit is that polarimetry is a differential measurement, so calibration of a polarimeter does not require establishing a set of astronomical standards, as is the case for photometry. Also, as the Earth's atmosphere does not affect the polarization state of incident radiation, high-precision polarimetry is much easier than photometry (an exception to this will be discussed later). In practice, most astronomical polarimeters achieve sensitivities for fractional polarization of $\sim 10^{-4}$, sufficient for many applications in night-time astronomy, although solar astronomers more regularly work with fractional polarizations as low as $\sim 10^{-5}$. Polarimeters that achieve parts per million, or better, although not especially difficult to build, are rather specialist and normally employ very fast modulation to achieve such sensitivities.

Interstellar polarization

Although the measured polarization of the Sun is low, this is unusual: virtually every other object in the sky has a higher polarization. Our nearest neighbour planets, seen in reflected light from the Sun at visible and near-infrared wavelengths, have polarizations that can be as high as several tens of per cent, depending on the angle between

the Sun, the planet and the Earth. One of the earliest applications of polarimetry was to study the nature of planetary surfaces and atmospheres. If the Sun were much further from the Earth a higher polarization would be measured, which would increase with distance. This *interstellar* polarization is produced by dielectric dust grains, typically $\sim 0.1 \mu\text{m}$ in size, that pervade interstellar space and attenuate and redden the radiation. They also produce some polarization by absorption, so at least some of the interstellar grains must be aligned, and hence must be non-spherical. How the grains are aligned has been the subject of many papers (e.g. those of Alex Lazarian) and it is probable that different mechanisms operate in different environments.

In the early 1970s it was proposed that high spin rates for dust grains, which aid grain alignment, could be produced by radiative torques. Largely forgotten for several decades, the mechanism has been reinvestigated and is now thought to be an important process. A key feature of grain alignment that is well established, is that the short axis of the grains invariably aligns with the local magnetic field (that is, the grains do *not* act like compass needles). This arises from the rapid precession of grains about the magnetic field, arising from the magnetic moment induced in the paramagnetic dust grain. Radiation with the electric field vector parallel to the long axis of the grain is preferentially absorbed, leading to a net polarization parallel to the grain short axis, and hence along the direction of the magnetic field. The process is often referred to as dichroic absorption. This differential extinction

Basic physics of polarimetry

The polarization state of radiation is, by convention, defined by the behaviour of the electric field. In the case of unpolarized radiation, the electric field orientation behaves in a random manner. For polarized radiation, the tip of the vector that represents the instantaneous electric field traces out an *ellipse*, a *circle* or a *straight line*, and the radiation is said to be *elliptically*, *circularly* or *linearly* polarized, respectively, with circular and linear polarization being particular cases of the more general elliptical form.

Degrees of polarization p can take any value from 0 to 1, and thus a mathematical description is required that can accommodate zero, complete and partial polarization. The most convenient and most widely used

parameterization for monochromatic light is due to Sir George Stokes, who used a four-vector representation of radiation with components I , Q , U and V .

The link between the Stokes parameters and the geometry of a polarization ellipse is given by $I = a^2$, $Q = a^2 \cos 2\beta \cos 2\theta$, $U = a^2 \cos 2\beta \sin 2\theta$, $V = a^2 \sin 2\beta$

where a represents the ellipse size, $\tan \beta$ the ratio of the minor to major axes ($\beta = 0$ for linear and $\pi/2$ for circular polarization), and θ is the orientation of the ellipse. For linear polarization the ellipse collapses to a straight line and θ is known as the position angle of polarization, essentially giving the preferred angle of the radiation's electric field,

as projected onto the plane of the sky. By convention this is measured from north, with increasing values rotating eastwards.

The degree of polarization p , linear polarization p_{lin} , circular polarization p_{circ} , polarized intensity I_p and θ are given by:

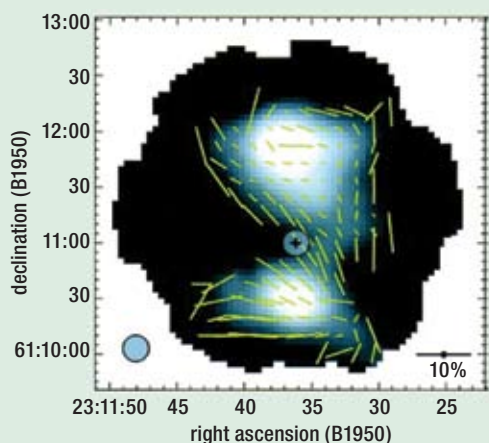
$$p = \frac{\sqrt{Q^2 + U^2 + V^2}}{I}, \quad p_{\text{lin}} = \frac{\sqrt{Q^2 + U^2}}{I}, \quad p_{\text{circ}} = \frac{V}{I},$$

$$I_p = I \times p, \quad \theta = 0.5 \tan^{-1} \left(\frac{U}{Q} \right),$$

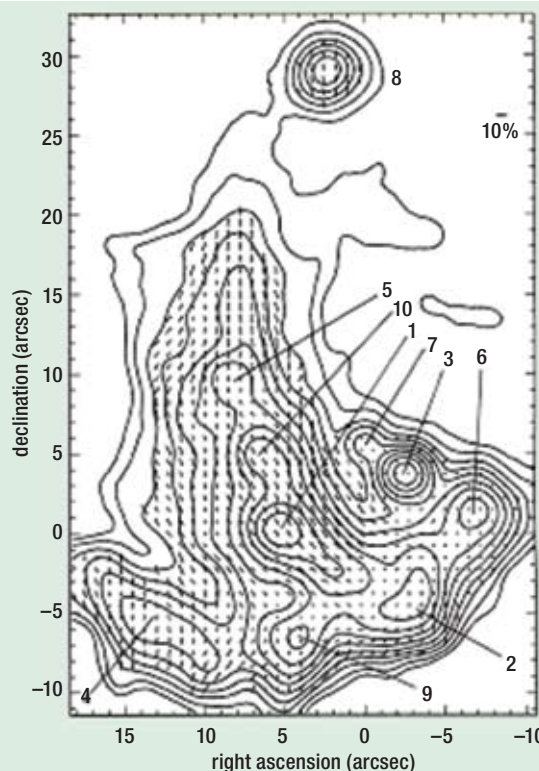
the sign of V gives the handedness of the circular polarization.

Taken from an article on imaging polarimetry by James Hough in the Encyclopaedia of Astronomy and Astrophysics, Nov. 2000.

2: Polarization E-vectors of the 850 μm continuum emissions for NGC 7538 superposed on the surface brightness map (Momose *et al.* 2001); the length of each line is proportional to the polarization degree. The direction of magnetic field is orthogonal to the E-vectors for polarized emission.

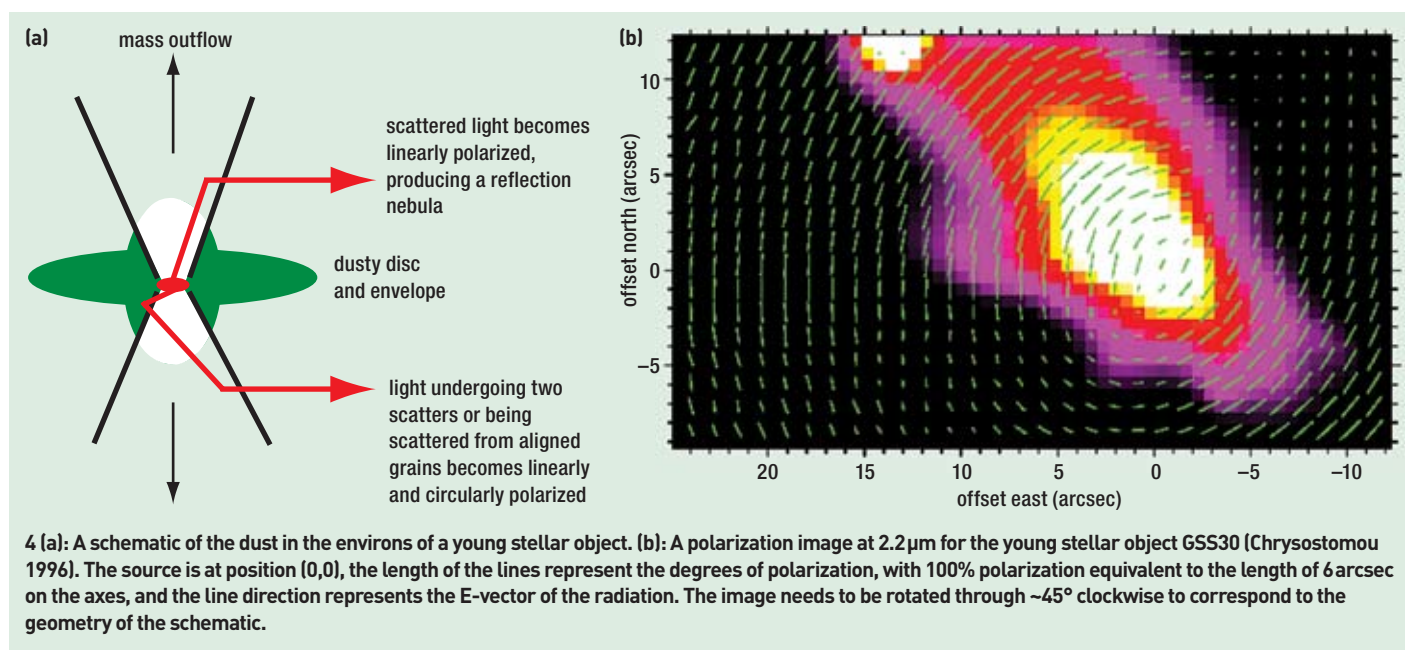


3: Surface brightness contours at 12.4 μm in the central region of SgrA overlaid with vectors orthogonal to the emissive polarization and thus denoting magnetic field directions. The numbers identify particular features in this region (Aitken *et al.* 1998).



of starlight can be used to map the direction of magnetic fields, or at least its projection on to the sky plane, and has been used to map the magnetic field in our own galaxy. The wavelength dependence of interstellar polarization $P(\lambda)$, appears to be the same for lines of sight to all stars, and just two parameters are needed to fully describe it: the wavelength at which the polarization is a maximum, λ_{max} , ranging from 0.3–0.8 μm with a mean value of $\sim 0.55 \mu\text{m}$; and the maximum polarization itself, P_{max} , which depends on the number of dust grains along the line of sight to the star and the efficiency with which the grains are aligned. $P(\lambda)$ is simply given by $P_{\text{max}} \exp(-1.15 \ln^2[\lambda_{\text{max}}/\lambda])$, which describes the famous Serkowski curve. Although there have been a few modifications over the years, the original equation is sufficiently accurate for many purposes. Figure 1 shows a typical interstellar polarization and extinction curve along the line of sight to a heavily reddened star. Note how the very large extinction peak at $4.6 \mu\text{m}^{-1}$ has no feature in the polarization curve. This implies that the graphitic carbon particles, believed to be responsible for the extinction feature, do not contribute to the polarization and are not therefore aligned.

Polarization measurements at submillimetre and millimetre wavelengths have become increasingly important over the past 10 years or so. At these longer wavelengths the aligned dust grains produce polarization in emission, rather than absorption, with the E-vector now perpendicular to the local magnetic field. Polarization observations, principally with the SCUBA camera on the James Clerk Maxwell Telescope, Mauna Kea, Hawaii, have been used to map the magnetic fields in dusty molecular clouds where stars are being formed, with these fields believed to play an important role in most phases of star formation, including the initial collapse of the cloud



and the ubiquitous outflows. Figure 2 shows the polarization at $850\mu\text{m}$ in the star-forming region NGC 7538 (the length of the line indicates the degree of polarization and the direction gives the direction of the E-vector, which is perpendicular to the magnetic field).

The same technique, but using polarimetry at mid-infrared wavelengths, was used by Aitken and collaborators to map the magnetic field structure in the northern arm and the east–west bar of the SgrA region of the galactic centre. In this region, the grains are sufficiently warm that at $12.4\mu\text{m}$, the wavelength of the observations, the emissive component of polarization is larger than the absorptive component produced by the intervening interstellar medium (figure 3). Furthermore, at these shorter wavelengths the spatial resolution is relatively high. Aitken shows that the physical conditions in the ionized filaments of the central parsec leads to a very uniform grain alignment so that the observed degrees of polarization can be used to measure the angle between the magnetic field and the line of sight. In this way the three-dimensional structure of the magnetic field was partially reconstructed, the first ever such application of polarimetry, and showed that the northern arm and east–west bar do not define an orbital path or spiral arm but rather represent a tidally stretched structure in free fall about SgrA*.

Scattering

Even if the interstellar polarization can be ignored, many sources of radiation would still show appreciable polarization. For example, synchrotron and cyclotron radiation produce linear and circular polarization respectively. However, it is the polarization produced by material around a star that perhaps provides most current interest. This could be from a protoplanetary disc or a debris disc – a circumstellar disc of dust created

by the collisions of planets and minor bodies such as asteroids, and believed to be responsible for the disc around the star β Pictoris. Polarization is produced when light from the star is scattered by material in the disc, with the position angle of polarization usually perpendicular to the plane of the disc, the degree of polarization depends on the inclination of the disc, and the wavelength dependence of polarization gives information on the size of the scatterers. Because the scattered light properties of dust are more easily observable than the planets themselves, debris discs provide an indirect means to study planets and planet formation around other stars.

In principle, however, polarimetry can be used to observe planets around other stars. To date, extrasolar planets have been detected mostly by indirect means, principally through radial velocity measurements of the central star or, far less frequently, through reductions in brightness of the star as a planet transits. Recently, the Spitzer Space Telescope has been used to observe the reduction in thermal infrared flux during secondary eclipse, when the planet passes behind the star. To date, however, there are no detections of the reflected light from planets, and for the so-called “hot Jupiters” – planets with sizes similar to Jupiter but orbital radii less than 0.1 AU – there is little prospect, in the foreseeable future, of being able to spatially resolve them from the very much brighter central star. In order to study their atmospheres, very high sensitivity observations have to be made to separate the small reflected (polarized) light from the very much larger direct (unpolarized) star light.

For ground-based observations, as explained earlier, polarimetry offers many advantages, although the expected maximum fractional polarization, as a hot Jupiter orbits a star, is only a few parts in a million. At the University of Hertfordshire we have designed and constructed

a polarimeter specifically to detect the polarization signature of extrasolar planets, achieving polarization sensitivities on very bright stars of around 10^{-7} , using the William Herschel Telescope on La Palma. In these cases, changes in brightness as the planet orbits the star are expected to be $\sim 100\mu\text{mag}$, far too small to be observed from the ground. To date we have not made a positive detection of the polarization, but we have put tight limits on the (low) albedo of two extrasolar planets. During these observations we have discovered that Saharan dust in the atmosphere, not infrequent in the summer months over the island of La Palma, can produce fractional polarizations of around 10^{-5} , showing that, under certain circumstances, atmospheric conditions can affect polarization measurements. We believe that the dust is producing polarization through differential extinction, implying that the dust grains are aligned, which has implications for radiative transfer in the atmosphere as well as high-sensitivity polarimetry.

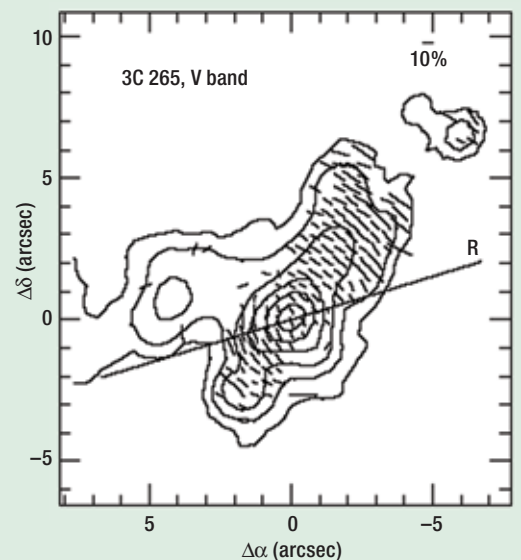
Some objects are surrounded not just by thin discs but by geometrically and optically thick tori and in some cases even more extended dusty envelopes. The optical depth can be so high that the central object cannot be viewed directly, at least from some directions. Examples of these are the early phases of star formation and active galactic nuclei. In most cases, outflows along the rotation axis of the system produce a cavity such that the density of dust is very much lower along the outflow axis than in the equatorial plane, where the optical depth can be so high that the object cannot be observed directly at optical and near-infrared wavelengths. Photons, however, can escape from the central source and be scattered to us by dust (in the case of stars) or electrons and/or dust (for AGN), producing beautiful reflection nebulae that can be spatially resolved for galactic sources (figure 4). Even for

distant radio galaxies such as 3C265, redshift 0.811, the very bright nucleus (a hidden quasar) illuminates the galaxy, which then appears as a giant reflection nebula with polarizations as high as 10%, despite dilution by stars in the galaxy (figure 5). The polarization pattern can be used to determine the location of the obscured source (where the normals to each polarization vector intersect), the degrees of polarization in the two lobes of the reflection nebula can be used to determine the inclination of the system, and the wavelength dependence of polarization can be used to determine the nature of the scatterers.

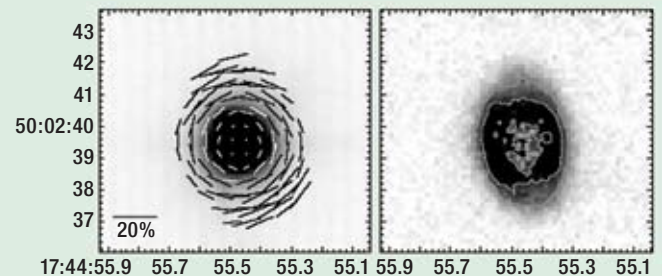
One of the best known examples of the diagnostic power of polarimetry has been in the unification of (at least some) active galactic nuclei, for example Type I and Type II AGN. The former are characterized by the presence of both broad and narrow emission lines in their spectra, whereas the latter only appear to have narrow emission lines, giving the impression that there are two distinct categories of AGN. But the polarized flux spectrum of Type II AGN – that is, the flux spectrum multiplied by the polarization – clearly shows the presence of broad lines for many objects. This led to the unification of Type I and II AGN and the recognition that the apparent difference is merely caused by the angle at which the system is viewed, with a geometrically and optically thick torus obscuring a direct view of the region in which the broad emission lines are produced (close to the central nuclear engine), for many lines of sight. The broad emission lines are scattered to us by particles, usually electrons, above the torus. For electron scattering, the polarized flux spectrum gives the flux spectrum of the obscured source, as electrons do not change the spectral shape of the scattered radiation. Further, a comparison of total and (scattered) polarized flux provides views of a source from different angles, whether the source be obscured from direct view or not; velocity-resolved spectropolarimetry enables the geometrical and velocity relationship between the radiation source, scatterer and observer to be determined without spatially resolving the source, giving effective spatial resolutions far higher than can be achieved even with optical interferometers. This very powerful diagnostic tool is used to study discs around stars. For example, Vink *et al.* (2005) used H α spectropolarimetry of T Tauri stars to show that a compact source of line photons is scattered off a rotating accretion disc, providing detail that is not possible with other techniques.

At the late stages of stellar evolution, many stars lose a significant amount of material, to form a circumstellar shell. This is often difficult to see because it is so close to the very bright star. However, in polarized flux the shell can be seen easily because the star, although bright, has effectively zero polarization; it produces very little polarized flux. The shell, although faint, has a

5: V-band imaging polarimetry of the radio galaxy 3C 265. Polarization vectors are superimposed on the total intensity contours. The solid line marked with an R indicates the orientation of the radio axis which is not aligned with the symmetry axis of the polarization in this object. (Tran *et al.* 1998)



6: Polarization of the protoplanetary nebula IRAS 17436+5003 in the J-band (Gledhill *et al.* 2001). The left panel shows the total flux image with polarization vectors superposed. The right panel shows the polarized flux, with the central star effectively blanked out leaving the highly polarized circumstellar shell.



high degree of polarization and hence relatively high polarized flux. Figure 6 shows a very nice example of this for the protoplanetary nebula IRAS 17436+5003. Imaging a faint object even closer to a very bright star, for example an extrasolar planet, is technically very demanding, with the main limitation not the intrinsic faintness of the nearby object, but 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 multi-wavelength 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.

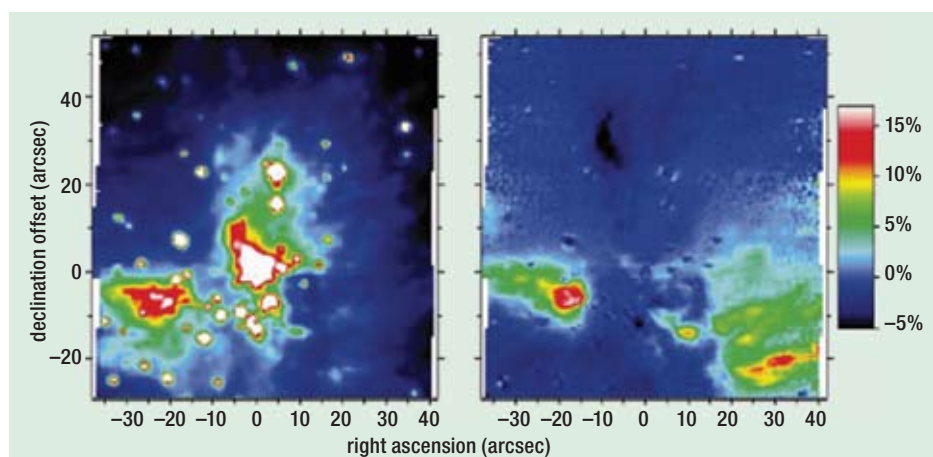
An alternative approach is to use the inherent differential nature of dual-beam polarimetry, where the atmospherically scattered speckle patterns are indistinguishable in the two orthogonal polarizations. Thus the difference image, constructed from orthogonal polarizations, removes the scattered light leaving a polarized brightness image of the planet or circumstellar disc, although a high polarization accuracy is still needed as the brightness of the planet or disc is much lower than the atmospheric speckle halo of the star. This technique is proposed for the

future ESO PlanetFinder (Gratton *et al.* 2004).

Circular polarization

Most astronomical observations use linear polarization, but circular polarization (CP) can provide many valuable diagnostics. CP is produced when linearly polarized light is scattered (e.g. in multiple scatters), so here the CP depends not only on the last scatter but also on the prior polarization state of the radiation (i.e. the polarization history of the photons). This process usually produces relatively low degrees of CP (1% or less), but if radiation, of any state, is scattered from aligned dust grains then much higher CP can be produced. Another way of producing CP is when linearly polarized light passes through a medium of aligned grains whose alignment twists along the line of sight, effectively by conversion of Stokes U to Stokes V by birefringence (see box, p3.32). When the linear polarization is high, as can occur for example with reflection nebulae, high degrees of CP (tens of per cent) can be produced by this process.

The discovery several years ago, by my own group, of large degrees of CP in the central regions of the Orion Nebula (figure 7), a site of extensive star formation, provides a possible explanation for the origin of homochirality on Earth. All amino acids (bar one) are chiral, occurring as two mirror image forms, or enantiomers.



7: Circular polarization image of the OMC-1 star-forming region in Orion at $2.2\mu\text{m}$. Total intensity is shown on the left with the bright Becklin-Neugebauer (BN) object at co-ordinate (0,0). Percentage circular polarization is shown on the right, from -5% (black) to +17% (white). (Bailey *et al.* 1998)

Amino acids in all living organisms are homochiral and use just one enantiomer. It is thought that life can develop, through self replication, if one enantiomer only is used; the origin of such homochirality is one of the most long-standing problems in understanding the origins of life. In the laboratory, significant enantiomeric excesses can be produced by UV CPL light (CPL), which preferentially destroys molecules of a particular handedness (asymmetric photolysis); autocatalytic reactions can further increase the enantiomeric excess. The problem is finding a suitable source of CPL outside the laboratory. The discovery of large degrees of CPL in Orion, where stars – and presumably planets – are forming, could be a clue to the origin of homochirality on Earth. Our own solar system is most likely to have formed in a region similar to that found in Orion. Bailey (1998) proposed that the CPL produced an excess of one enantiomer in prebiotic molecules, and that these were then delivered to Earth in the heavy bombardment period of the Earth's early history, and acted as seeds for the development of life. Although the observed CPL is at near-infrared wavelengths, models predict that there will be significant amounts of UV CPL, necessary for significant asymmetric photolysis. The discovery of life elsewhere in the universe has become one of the key problems of scientific endeavour and establishing robust biomarkers is an essential element in that programme. As homochirality is a requirement for self-replication, presumably including unknown life-forms, chiral signatures arising from enantiomeric excesses, could be used as a unique biomarker. Light scattered from biological particles will be circularly polarized and although the effect is generally small it is usually far higher than any CP from abiotic materials and, furthermore, biotic materials will have characteristic spectral signatures in CPL.

Circular polarimetry has been used for many years to study the Zeeman effect and thereby measure the strength of magnetic fields. Solar

astronomers in particular have used the magnetic field diagnostic techniques based on the Zeeman and Hanle effects to study solar magnetic fields. Recently, in some beautiful observations, Donati *et al.* (2005) have used high spectral resolution circular spectropolarimetry to show the magnetic field strength of about 1 kG in the core of the bright protostellar accretion disc in FU Orionis. Such observations are very important in determining the role magnetic fields play in accretion discs and their associated winds and jets.

To higher redshifts

Polarimetry is playing a key role in the high-redshift universe. Gamma-ray bursts (GRBs) are the most energetic events in the universe and polarization of the gamma rays themselves is a key diagnostic of the GRB mechanism. Equally important in understanding the nature of GRBs is the polarization of the afterglow at optical and near-infrared wavelengths that provides geometrical information about the unresolved system and the evolution of the expanding fireball. A novel way of using polarimetry to measure the distance to stellar outbursts, including supernovae, was proposed by Sparks (1994). Circumstellar light echoes, where light is reflected from interstellar dust, are seen around some outbursts. In principle the scattering angle can be calculated from the observed polarization and, for 90° scatters, the distance from the source to the scatterer can be calculated easily from the light travel time, enabling the distance to the outburst to be calculated by simple geometry.

The first detections of the polarization of the Cosmic Microwave Background (CMB) were made a few years ago by the DASI interferometer at 30 GHz, operating at the south pole. CMB photons last interacted with matter 300 000 years after the Big Bang, about 15 billion years ago, through Thomson scattering of photons off free electrons. As the well-measured CMB anisotropy has a quadrupole component, the scattered radiation will be polarized and the

polarization will provide further information on the dynamics of the early universe and the nature of primordial density fluctuations. The polarization is very small, being just a few per cent of the temperature anisotropies, which in turn are very small. Interestingly, one of the problems in measuring the polarization of the CMB arises from the polarized emission from galactic dust which we referred to above.

A tool for the future?

As I hope this article has shown, polarimetry has played and continues to play a very important role in many areas of astronomy. Despite this, and the relatively low cost of including polarimetry in imagers and spectrometers, there are potential problems in ensuring polarimetry remains a standard technique on future telescopes. One particular problem is that polarimetry is best carried out at the unfolded Cassegrain focus, as otherwise oblique reflections can change the polarization state of the incoming radiation, most obviously introducing linear polarization of a few per cent at visible wavelengths for a 45° reflection (so-called instrumental polarization). Unfortunately, an unfolded Cassegrain focus is not always available for instruments where polarimetry would be a natural technique. In a similar vein, the increasing use of adaptive optics to provide higher spatial resolution, itself very important for polarimetry, again introduces oblique reflections. While trying to secure the optimum conditions for polarimetry is an important goal, there are ways in which some of these problems can be overcome. For example, instrumental polarization can be reduced by the use of compensating mirrors and retarders, and adaptive secondary mirrors can be used to improve spatial resolution without introducing additional reflections. It would be a significant loss if astronomers are not able to extract the maximum information from the electromagnetic radiation incident on our telescopes, and this can only be achieved through polarimetry. ●

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