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Polarimetry in the infrared: what can be learned?

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Abstract

At near-infrared wavelengths many of the diagnostics familiar from imaging and spectropolarimetry in the optical and UV are extended to include regions suffering dust extinction and unobservable at shorter wavelengths, and for high-z objects many important spectral lines are shifted into the near-infrared. In the mid-infrared and far-infrared, polarised flux is largely produced by emission and absorption from non-spherical dust grains aligned with the local magnetic field, thereby giving information on the properties of the grains, their alignment mechanisms and the magnetic field structure. Polarised radiation from the synchrotron process occurs at all infrared wavelengths.

Keywords: Polarimetry; Infrared; Astronomy; Imaging; Spectropolarimetry

Contents

1. Introduction

Polarimetry has played an important role in astronomy for several decades. Initially polarimetry was restricted largely to optical and UV wavelengths as the high signal to noise required for accurate polarimetry was limited by the relatively poor sensitivity of detectors and the much higher

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backgrounds experienced at infrared wavelengths. The introduction of area detectors first occurred at optical wavelengths and then near-infrared wavelengths (NIR), and it is only in the last few years that these detectors, with good quantum efficiency, acceptable read noise and adequately low dark currents have become available at mid-IR (MIR) wavelengths, opening up the possibility of long-slit spectropolarimetry and efficient imaging polarimetry at these wavelengths. Note that in the mid-infrared the limiting factor in many situations is the large and often variable background; for polarisation work the problem of variability is avoided with a two-beam system, in which orthogonal states are measured together, and the use of modern, low emissivity large telescopes reduces the effect of the background. This review covers the diagnostics available from imaging and spectropolarimetry for wavelengths ranging from 1μm to several hundred microns (the sub-millimetre). It should be noted that polarimetry is mainly restricted to ground-based observations, particularly for wavelengths long-ward of 2μm.

2. The near-infrared

This covers the wavelength range 1–5μm, with atmospheric windows at 1.2, 1.6, 2.2, 3.5 and 4.8μm. Diagnostic tools are similar to those available at optical wavelengths but advantage can be taken of the far lower dust extinction, and for moderate redshifts many UV and optical lines are shifted to the NIR. Even if the diagnostics are similar, coverage of a wide wavelength range is important in order to construct adequate models of most astrophysical processes.

The production of polarised flux is intrinsic to a number of radiation processes. For example, electrons with low values of v/c in a magnetic field produce circularly polarized (cyclotron) radiation. For polars (AM Her binaries), with typical magnetic fields of 20–60 G, the fundamental harmonic is at wavelengths of ∼1–5 μm, and thus the more usual observations at optical wavelengths study only the higher harmonics [1]. Relativistic electrons produce synchrotron radiation, which is linearly polarised, with E perpendicular to B. For core-dominated radio sources in Active Galactic Nuclei, Doppler-boosted emission from relativistic jets produces high and variable polarisation from the UV to the submillimeter/millimeter wavelengths [2]. Studies of these sources requires either multiwavelength observations and/or observations that give good temporal coverage of the variability. Of particular interest in the NIR is the reduction in the degree of polarisation at ∼3–5 μm, produced by emission from hot dust located close to the AGN. The polarised flux spectrum, however, mimics the spectrum of the polarised synchrotron radiation, provided the dust emission is unpolarised.

Polarised radiation is also produced by non-spherical dust aligned with the local magnetic field. Although the mechanism(s) producing the alignment is not always well established, the grain orientation will be controlled by the field. In the Interstellar Medium, grains acquire rotational energy in equipartition with the ambient gas, with typical spin frequency on the order of MHz. Because of mechanical hysteresis grains spin about their short axis and, through the Barnet effect [3], develop a magnetic moment in this direction; and their spin axes will therefore precess about the field direction. In itself this does not produce alignment but it ensures that the direction of any anisotropy in the distribution of spin axes is controlled by the field [4,5]. In emission the grains radiate with **E** vectors preferentially perpendicular to **B**, while the polarisation produced by absorption is parallel to **B**; polarisation produced in this way is often referred to as dichroic emission or absorption, and

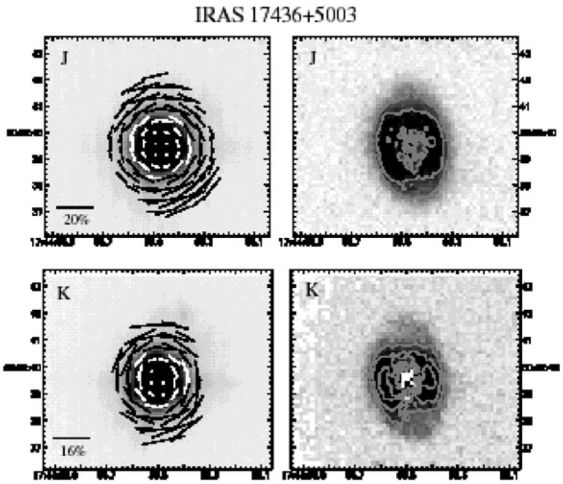

Fig. 1. Degrees of polarisation and the polarised flux in the J (1.2 μm) and K (2.2 μm) bands for IRAS 17436+5003 [14].

the process as dichroism, since it is due to the medium having different properties in two orthogonal directions. Aligned silicate grains will usually produce polarisation through absorption in the NIR but, close to their sublimation temperature of $\sim 1000\,K$, will emit radiation at wavelengths as short as ~ 2 μm, although the study of polarised emission from aligned grains is usually studied at wavelengths of 10 μm and longer.

Up to a few microns, most polarimetry in the NIR is concerned with polarised flux produced by scattering. Scattering off electrons or Rayleigh-type grains (grain size much shorter than the wavelength of radiation) produces linear polarisation with degree independent of wavelength at a given angle. Observing scattered radiation allows normally obscured regions to be viewed (e.g. in an AGN or young star, radiation can escape along the poles of an obscuring dusty disk or torus, and be scattered into our line of sight by dust and or electrons located along the polar directions). Spectropolarimetry allows the study of the velocity relationship, as well as geometrical relationship, between the radiation source, scatterer and observer without spatially resolving the source. Lastly, a comparison of total and (scattered) polarised flux provides views of a source from different angles.

Although far less well studied, circular polarisation can provide many important diagnostics. It is produced by the scattering of linearly polarised radiation off non-Rayleigh particles and thus can give information on the last two photon scatters. When combined with linear polarimetry it constrains the physical and chemical properties of dust grains far more than linear polarimetry alone, being a different function of grain size and largely dependent on the imaginary (absorptive) component of the grain refractive index. Circular polarisation can also be produced by the scattering of radiation (of any state) off aligned grains, although particles must be absorbing if they are in the small particle limit [6,7].

Another secondary process is dichroic absorption, and it is this process that leads to the well-known interstellar linear polarisation curve, first identified empirically by Serkowski at optical wavelengths [8] and then later refined to include wavelengths up to ~ 2 μm [9]. Circular interstellar polarisation, first observed by Martin in 1972 [10] has been largely neglected. The theoretical treatment of the coincidence in wavelength of peak interstellar linear polarisation and the wavelength where the interstellar circular polarisation changes sign was first discussed by Martin [11], and more recently reviewed by Voshchinnikov [12] who concludes that this particular wavelength provides very little information about the absorptive properties of interstellar grains but the general wavelength dependence of circular polarisation can help to determine dust properties. Between 3 and 5 μm the interstellar linear polarisation better fits a power law [13]. Studies of interstellar polarisation give the (average) direction of the magnetic field along the line of sight to individual stars and the properties of the polarising dust grains.

A good example of the usefulness of imaging polarimetry at NIR wavelengths is shown in Fig. 1, in which the degrees of polarisation and the polarised flux for the proto-planetary nebula IRAS 17436 + 5003 are presented [14]. In polarised flux the central star, which is unpolarised, is effectively masked out, revealing the structure of the circumstellar envelope. Modelling of the wavelength dependence of the polarisation can provide information on the dust grains within the envelope.

3. Mid-infrared and far-infrared wavelengths

The MIR covers 5–50 μm, with atmospheric windows at 10 and 20 μm, and the FIR extends to a few hundred microns with atmospheric windows at 350 and 450 μm. Most of the polarimetric astrophysics at these wavelengths is related to the dichroic absorption and emission associated with aligned dust grains, and to the study of the role of magnetic fields in astrophysics. Dust grains play a key role in virtually all astrophysics and are the catalysts for much of cosmic chemistry. The ability of dust grains to 'align' with their short axis processing around the direction of the local magnetic field provides information on the geometry of the magnetic fields, essential in understanding the processes of accretion, disk formation and mass outflow, for stars and AGN. Thus determining the properties of dust grains remains of fundamental importance in astronomy.

Spectropolarimetry is a powerful diagnostic tool for determining the chemical and physical characteristics of dust grains and the alignment processes. Polarisation produced in absorption P_{abs} and in emission P_{em} can be expressed in terms of the absorption of radiation in the x and y directions (τ_x, τ_y), by (e.g. Hildebrand [15])

$$P_{abs} = (e^{-\tau_x} - e^{-\tau_y})/(e^{-\tau_x} + e^{-\tau_y}) = -\tanh\{(\tau_x - \tau_y)/2\} \approx -(\tau_x - \tau_y)/2,$$

$$P_{em} = \{(1 - e^{-\tau_x}) - (1 - e^{-\tau_y})\}/\{(1 - e^{-\tau_x}) + (1 - e^{-\tau_y})\} \approx (\tau_x - \tau_y)/(\tau_x + \tau_y).$$

The negative sign for P_{abs} indicates that the direction of polarisation is orthogonal to that for P_{em}. For optically thin emission:

$$P_{em}(\lambda) = -P_{abs}(\lambda)/\tau(\lambda), \quad \tau(\lambda) = \tfrac{1}{2}(\tau_x + \tau_y).$$

P_{abs} is characterised by a polarisation that increases with optical depth within a solid state resonance such as that at 9.8 μm produced by the stretching mode of the Si–O bond and at 20 μm produced by the bending mode of O–Si–O bonds in silicates [15]. A particular characteristic of P_{abs} is that the peak of polarisation occurs at a slightly different, usually longer, wavelength than the peak in extinction because extinction and polarisations are different functions of τ_x, and τ_y [16]. This has

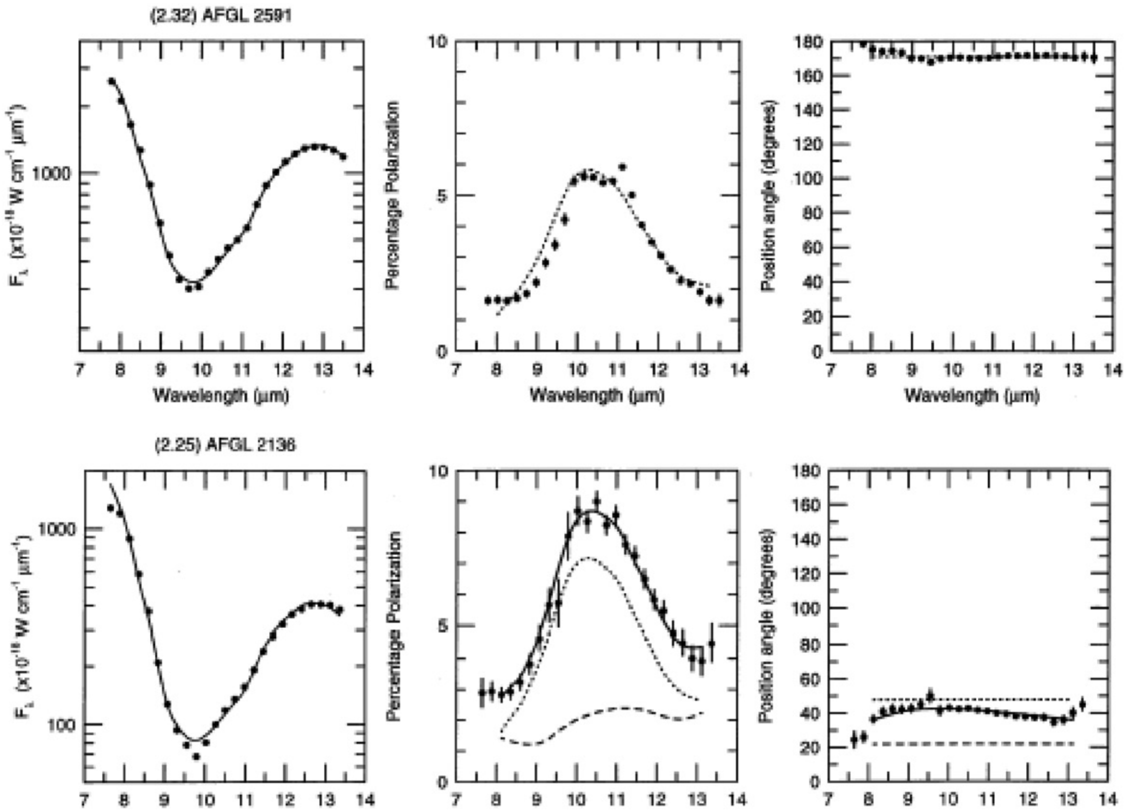

Fig. 2. (a) spectropolarimetry of the silicate feature in the 10 μm atmospheric band for AFGL2591. The left-hand box shows the total flux spectrum, the middle-box the degree of polarisation and the right-hand box the position angle of polarisation. The polarisation spectrum shows a feature at ∼11.2 μm attributed to annealed silicates [17]. The dotted line in this figure is the polarisation spectrum of BN (normalised to the same peak height); (b) as for (a) for AFGL2136 [4]. The polarisation has been modelled assuming an absorptive (dotted line) and an emissive (dashed) component.

been demonstrated for icy mantles on grains in the NIR [16] and for silicate grains in the MIR [4]. Absorptive polarisation is roughly proportional to optical depth and so a significant optical depth of material is required to give polarisation; quite high polarisations can occur with large optical depths and well-aligned grains, for example the heavily obscured Becklin–Neugebauer (BN) object in Orion has a 10 μm polarisation of 12.5% [4]. Conversely emissive polarisation (P_{em}) is independent of optical depth so long as this is small, so that polarisation can arise from vanishingly small amounts of material along the line of sight. Its spectral form is characterised by a weak tilde shape (the ratio of absorptive polarisation to extinction) within a resonance and becomes largely wavelength independent beyond 20 μm, the last significant resonance in grain materials. Longwards of 100 μm or so, most diffuse sources are optically thin and polarimetry samples the whole depth of the source.

The spectrum of absorptive polarisation, unlike the intensity spectrum, is independent of the nature of the underlying source, provided the latter is not polarised, and its position angle is constant with

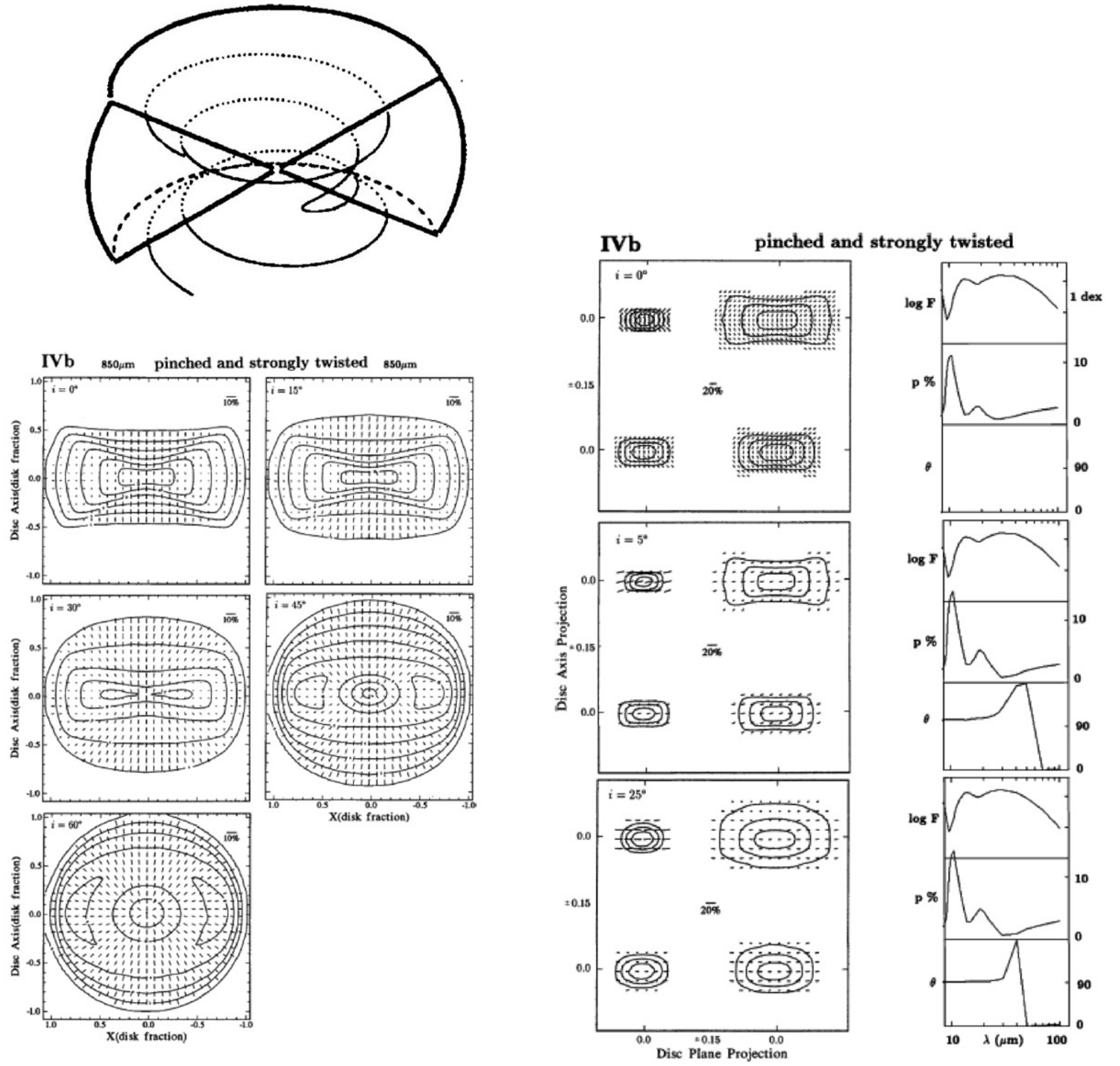

Fig. 3. Top left-hand shows the pinched and strongly twisted field geometry; and top right-hand shows the calculated polarisation images at 10, 13, 18 and 22 μm (anticlockwise starting in the top left-hand corner) for inclinations 0°, 25°, and 45° of the dusty disk, together with the low-resolution spectropolarimetry; and bottom left-hand shows the polarisation images expected at 850 μm [19].

wavelength. Further, the position angle remains independent of wavelength even if the alignment direction twists along the line of sight, so long as the grain chemistry is not fractionated along the line of sight. This makes it easy to detect if a polarised source contributes since it will disturb the constancy of the position angle. Spectropolarimetry is therefore a powerful probe of grain chemistry and, since it is a different function of the grain optical constants and geometry than extinction, provides additional independent constraints. An example of this is shown in Fig. 2(a) that shows the polarisation of the young stellar object AFGL2591 [17], in which a narrow polarisation feature at 11.2 μm has been attributed to annealed silicates while the flux spectrum shows only a small change of slope at this wavelength. The dotted line in this figure is the polarisation spectrum of BN (normalised to the same peak height), which itself supplies a good fit to most other objects studied [4]. Should the underlying source be polarised, for instance if it contains warm aligned grains, then this is usually detectable through a wavelength dependence of position angle as the two alignment directions are likely to differ. An example of this can be seen in Fig. 2(b) that shows the spectropolarimetry of the young star AFGL2136, which is modelled in terms of an absorptive (dotted line) and emissive (dashed line) component [4].

The MIR is able to take particular advantage of the recent introduction of the 8-m class telescopes. For diffraction-limited observations the 8-m telescopes give better spatial resolution, crucial for imaging polarimetry as unresolved **E**-vectors with different position angles can cancel out, and observations for background limited observations are sixteen times faster than with a 4 m telescope. Also, the low emissivity of the new generation telescopes, leads to a further gain in limiting sensitivity in the thermal infrared.

In recent years modeling has moved forward with the development of radiative transfer (RT) codes [16,18] that can include polarisation transfer for dusty clouds containing non-spherical grains, partially aligned by magnetic fields with various geometries [19]. Previous modelling has been confined to populations of aligned grains confined to two slabs, one emissive with an overlying absorptive component. One new treatment uses RT theory to find the temperature profiles in optically thick disks and follows the polarisation transfer for the four components of the Stokes vector. The polarisation images and spectra for a particular field geometry and set of inclination angles, i, are shown in Fig. 3 [19].

4. Conclusion

Polarimetry at infrared wavelengths is able to study the many regions in stellar, galactic and extragalactic astronomy that suffer dust extinction, and which are unobservable at shorter wavelengths. Spectropolarimetry at NIR wavelengths is a very important diagnostic tool for objects with high-z where the important UV and optical spectral lines are redshifted into the NIR. Dichroic absorption and emission (the latter important at wavelengths beyond $\sim$2 μm) can be used to determine magnetic field structures from the position angle of polarisation, and spectropolarimetry of the solid state features such as ices at wavelengths of 3–5 μm, and silicates at 10 and 20 μm, can be used to determine the physical and chemical properties of dust grains. The new generation of large telescopes ($\sim$8–10 m diameter), with low emissivity, and the availability of high quality area detectors at NIR and MIR wavelengths, promises a rich scientific return.

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