A mid-infrared polarization capability for the ELT

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ABSTRACT

Imaging- and spectropolarimetry in the thermal infrared ($\sim$ 5–30 μm) can inform us about two important open questions in modern astrophysics – namely the role of magnetism in the formation of stars, and the life-cycle of cosmic dust. These are key questions outlined in the document "A Science Vision for European Astronomy" by de Zeeuw & Molster (2007). Thermal IR polarimetry is the only technique that can peer into the heart of star forming cores, where an infant star heats its immediate surroundings to temperatures of several hundred Kelvin. The polarization itself is induced by a preferential alignment of the spin axis of cosmic dust grains, a process ultimately controlled by the ambient magnetic field. The spectrum is sensitively dependent on the grain optical properties, structure and shape, thus providing information not otherwise obtainable by conventional spectroscopy. The MIRI instrument on the JWST will not have a polarimetry mode, thus leaving open the possibility of an ELT mid-IR instrument being able to make substantial progress on these fundamental issues.

Before describing the advantages of a mid-IR spectropolarimeter on an ELT, we first present some preliminary results from our polarization observations with the TIMMI2 mid-IR instrument between 2004 and 2006. The experience gained with TIMMI2 – in terms of technical issues and observing strategy – will inform the design of any future instrument. Following this we will describe the science that could be done with an ELT instrument, and some of the basic design parameters. For instance, with a resolution of $\sim$ 70 milli-arcseconds (FWHM at 10 μm) it will become possible to resolve the magnetic field configuration in the circumstellar disks and bipolar outflows of young stars at a spatial scale of less than 10 AU in the nearest star formation regions. This will strongly constrain hydromagnetic models – the favoured means of extracting angular momentum and allowing accretion to proceed – for bipolar jets emanating from a range of compact astrophysical objects. Further, with a resolving power of order 200, and sensitivity of 100σ in 1 hour integration on a 0.5 mJy point source, the evolution of cosmic dust – and the governing physical and chemical processes – from its formation in old stellar outflows to its deposition in planet-forming disks, will become amenable to detailed polarization studies.

Keywords: thermal infrared, polarimetry, imaging, spectroscopy, magnetic fields, cosmic dust

1. POLARIZATION IN THE MID-INFRARED

Cosmic dust grains are in general non-spherical and spinning, caused by collisions with other grains and gas phase species. Through an interaction between an external magnetic field and internal magnetic moments, the rotation component along the grain long axis is damped, so that the grain ends up rotating about the axis of greatest moment of inertia (i.e. its short axis). Thereafter the short axes, and so the angular momenta, of the ensemble of grains can become aligned along a common direction by one of a number of potential mechanisms. This alignment is always ultimately controlled by the ambient magnetic field. See Ref. 1 for a review of grain alignment theory. In most, if not all, cases the angular momentum aligns along the field direction (see Ref. 2). Such preferential alignment along a common direction results in a dichroic effect, so that radiation passing through a medium of such grains, or emitted by the grains, becomes partially polarized. Thus, measurement of the polarization position angle can be related to the magnetic field direction projected onto the plane-of-the-sky, thereby allowing the study of how magnetism influences astrophysical processes.

In absorption the position angle of polarization is parallel to the magnetic field, whilst for emission it is perpendicular to the field. In the mid-IR both polarization processes can be present in a single observation, indicative of cold ($\leq$ 100 K) and warm ($\geq$ 200 K) dusty regions respectively. As shown in Ref. 3, because of their unique spectral form the two components can be separated (or unfolded), potentially providing information in the third dimension, i.e. along the line-of-sight, on the magnetic field.

Furthermore, the cross sections for absorption of radiation along the major and minor axes of a spheroidal dust grain peak at different wavelengths. The polarization is formed by the subtraction of these cross sections, in a sense amplifying any small differences, whereas the total absorption is simply proportional to their sum. As well as the specific grain shape – e.g. oblate versus prolate spheroids and their principal axis ratios – and the properties of any covering mantle, the cross sections are in turn sensitively dependent on the grain dielectric function across spectral resonances. This is a unique identifier of the responsible material. Therefore polarimetry, and especially spectropolarimetry, is a more powerful probe of dust grain physics and chemistry, and hence their governing processes, than is conventional spectroscopy.

There have only been a few instruments capable of measuring astronomical mid-IR polarization, most notably those built and maintained at UNSW@ADFA. These were the UCLS spectrometer[4] and the NIMPOL imager,[5] decommissioned by 1994 and 1998 respectively. So between about 1993 and 2001, and 1998 and 2001, there was no operating mid-IR spectropolarimeter or imaging polarimeter. In 2001 and 2002 some new observations were carried out with Michelle on UKIRT, e.g. imaging in Ref. 6 of the Galactic Centre and spectroscopy of several young stellar objects (YSOs) in Ref. 7, before it was moved to Gemini-N.[8]

Imaging polarimetry observations with the TIMMI2 instrument on the ESO 3.6 m telescope were executed in 2002. A description of this mode is given in Ref. 9, with some science results on the HII region G333.6-0.2 presented in Ref. 10. Spectropolarimetric observations were carried out in 2004, 2005 and 2006, after which TIMMI2 was decommissioned. Though still confined to a 4 m class telescope, the two instruments – TIMMI2 and Michelle with their 320×240 Si:As IBC (or BIB) arrays – already provided a hint of the potential advances that could be made with larger area and increased sensitivity detectors, and enhanced spectral resolution.

For instance, the polarization maps of SgrA[6] and G333.6-0.2,[10] shown in Fig. 1, traced the polarization across a larger area and to fainter flux levels than the corresponding images in Refs. 11 and 12. A three-fold increase in the spectral resolving power to ~ 150 also allowed more detailed investigation of dust mineralogy toward several targets, e.g. the massive YSO AFGL 2591[7] and others to be described below.

However, the bulk of the observations (but not all) were performed on sources that had already been detected by the UCLS or NIMPOL. This is even the case for the single publication thus far utilising an 8 m telescope in Ref. 8 of NGC 1068, though in this case the difference in quality between the 8 m and 4 m data is really quite dramatic. Exciting advances – not just on new objects but new *classes* of objects – await the *regular and routine* coupling of a mid-IR imaging- and spectropolarimeter on firstly an 8–10 m class telescope, and we hope later on an ELT. However, before we look at these potential advances we briefly digress to describe in more detail TIMMI2's spectropolarimetric performance, which has not been previously reported. We do so here for posterity and because lessons were learnt that could inform the design and operation of future instruments.

2. TIMMI2 MID-IR POLARIZATION OBSERVATIONS

We conducted 8–13 μm observations using TIMMI2 on the ESO 3.6 m telescope at La Silla in April 2004 during a three night combined commissioning and scheduled science run. The major aim was to search for trace silicate mineralogical features. Further commissioning and science observations were undertaken with Director's time in October 2005 and June 2006, and a scheduled science run was executed in January 2006. Standard chopping and nodding techniques were employed. The polarization is detected by observing a target at successive orientations of a cold wire grid analyser mounted inside the dewar. The wire grid was sequentially set at positions of 0° and 90°, and the intensities at these positions subtracted to determine one component of linear polarization, namely the Q Stokes parameter. The grid is then rotated to 45° and 135°, and observed intensities subtracted to produce the orthogonal polarization component, i.e. the U Stokes parameter.

TIMMI2 was different to other recent ground-based mid-infrared polarimeters – UCLS, NIMPOL and Michelle – in that the cold wire grid analyser also acts as the rotating modulator. Most previous instruments instead used a warm rotating half-wave plate on the telescope axis as modulator and a fixed wire grid inside the dewar as analyser. Reasons for the TIMMI2 arrangement, where the wire grid analyser was located just in front of the cold pupil stop, are given in Ref. 9. There are advantages and disadvantages to both techniques. In the case of

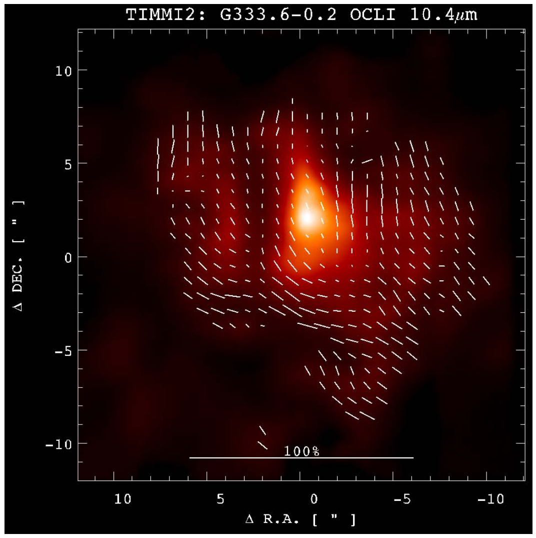

Figure 1. TIMMI2 mid-infrared polarization image of the HII region G333.6-0.2.[10]

TIMMI2 there was no additional warm – and therefore emissive – component in the beam, but such a set-up is more susceptible to instrumental polarization since the modulation occurs after several external and internal reflections. Further, it took longer to rotate the cold grid so the atmosphere must be stable over longer timescales (e.g. tens of seconds). This increased time for wire grid rotation also degraded the observational efficiency.

2.1 TIMMI2 observing strategy

In 2004 observing strategies of single, double and triple full rotations of the wire grid were performed per A and B beam in order to assess the mid-infrared polarimetric performance of La Silla. Increasing the number of rotations per beam obviously also lengthened the time between A and B beam subtraction, and therefore became increasingly reliant on stable atmospheric conditions. However, it also improved the overall observing efficiency by decreasing the total number of beam switches required to achieve the same (theoretical) S/N. Each object was observed using at least two of the three strategies, and consistent polarization signals were detected for the three strategies across the three nights. In the subsequent 2005 and 2006 runs we maintained the 'three rotations per nod' strategy, finding that the atmosphere above La Silla is suitably stable to ensure high quality 10 μm polarization observations, and that the 3.6 m is a clean mid-IR telescope.

In the first-time 2004 observations the spectropolarimetric performance of TIMMI2 itself was tested by observing intrinsically unpolarised, bright standard stars. These were α CMa, α Cen, γ Cru and η Sgr, and all were observed at least once per night. We also observed four science targets, namely the BN Object in Orion, AFGL 4176, RCW57 IRS1 and AFGL 2104. The first three sources are high mass YSOs for which the aim was to investigate the dust local to the object. On the other hand AFGL 2104 (WR 112) is a Wolf-Rayet star (WC9) which acts as a background continuum source to investigate dust absorption in the diffuse ISM. These four science targets have known (R $\sim$ 40) mid-infrared polarization spectra from the UCLS.[4] They range in 10 μm flux from $\sim$ 50 Jy (RCW57 IRS1) to several hundred Jy (BN), silicate optical depth τ of $\sim$ 1–2 (AFGL 2104) up to $\sim$ 3–5 (AFGL 4176), peak 10 μm polarization from $\sim$ 2% (AFGL 2104) to 13% (BN), and polarization mechanism (and therefore spectral shape) of pure absorption (BN, AFGL 4176, AFGL 2104) to pure emission (RCW57 IRS1). This range of parameters was chosen to stringently test TIMMI2's spectropolarimetric capability.

2.2 TIMMI2 data reduction

2.2.1 Spatial and spectral shifts

Although the 10 μm polarimetric conditions at La Silla were generally very good, several instrumental artefacts affected the observations, but which could be corrected during post-processing. The first, and least serious, was spectral and spatial shifts between the different orientations of the TIMMI2 internal wire grid analyser. In other words, the spectrum was shifted in both the horizontal (x, spectral) and vertical (y, spatial) axes of the array. These x and y shifts were up to 1–2 pixels. Since the fractional polarization is formed from a quotient between the Stokes parameters Q (and U) and total intensity I, the x-axis shifts introduced spurious features in the polarization spectrum, especially across narrow telluric absorption bands. These spectral shifts were corrected by interpolating the spectra at a tenth of a resolution element and performing a cross correlation between any one particular spectrum (used as the reference) and all other spectra. This yielded a fractional pixel offset which could then be applied to the spectra at subsequent wire grid orientations, after which subtractions and divisions could be performed to derive the polarization quantities. This correction proved quite adequate, although a remnant sharp feature may still be present around 9.6 μm, the position of the telluric ozone band.

The spatial shifts had already been noted in Ref. 9 in imaging data, where careful registration had to be performed. For the spectroscopy our first method to extract the spectrum was simple pixel summing across the spatial profile of the object. If these profiles were not well aligned with respect to each other then such pixel summing will add in noise. We therefore tried two methods, a cross correlation similar to that described above for the spectral shifts, after which pixel summing was used to determine the total signal, and simple Gauss fitting of the spatial profile where the total signal is just the area under the Gaussian. We found that the cross correlation plus pixel sum technique provided a better spectrum, likely because the spatial profile did not appear to be a true Gaussian. In any case, Gauss fitting could not be used for the cases where our object was extended in the mid-IR, such as RCW57 IRS1.

2.2.2 Instrumental polarization

The second artefact encountered during the TIMMI2 observations was due to instrumental polarization, P_{inst}. From the standard star observations TIMMI2 was found to have a relatively large and spectrally complex instrumental polarization. Fig. 2 shows the instrumental polarization spectrum obtained from the co-addition of 10 standard star spectra. All features in the spectrum from about 7.7 to 13.5 μm are repeatable and therefore real. This includes the 90° position angle change between about 9 and 10.5 μm, where Q and U change sign. A high P_{inst} was also seen in imaging data in Ref. 9, as well as in Ref. 10 where it was characterised in more detail in several of the TIMMI2 filters. Taking into account the filter widths, the behaviour of the instrumental polarization is qualitatively similar between the imaging and spectroscopy modes, namely $\geq 10\%$ at 8.6 μm, $\leq 4\%$ at 10.3 μm and $\geq 5\%$ above 11.6 μm. However, the imaging data did not reveal the 90° position angle change at $\sim$ 9–10.5 μm, perhaps due to the broadness of the 10.3 μm filter passband. The origin and spectral form of the TIMMI2 instrumental polarization is not currently understood, probably because it hasn't been attempted. But presumably it must be something common to both imaging and spectroscopy modes, and hence probably places the culprit upstream of the grid (as it should given that the modulation is provided by the grid). Obviously if the TIMMI2 model of measuring mid-IR polarization is ever implemented in another instrument its P_{inst} signature would need to be understood much better.

In the 2004 campaign the instrumental polarization position angle also varied from night to night, and even during a single night, indicating a rotation of the internal reference frame. Assuming the wire grid always returned to its same position at the start of an observation, and that it was well fixed in its mount, the position angle should not change and so this variation would be difficult to understand. However, following this run the TIMMI2 dewar was opened and it was discovered that the wire grid may indeed have been slightly loose in the mount, especially at cryogenic temperatures. It was then glued into place and the subsequent commissioning and science runs in 2005 and 2006 showed a highly reproducible instrumental polarization signature.

But for the 2004 data set the intra- and inter-night position angle variation would normally be a serious impediment to subtracting the instrumental polarization from science data, since they do not have the same "zero point". Fortunately, and against initial expectations, the large $\sim$ 50% P_{inst} feature at $\sim$ 8 μm becomes useful. This feature dominates any other polarization, P_{targ}, from the science target and can therefore be presumed equal in both the target and instrumental polarization spectra. So it can be used to rotate either one onto the co-ordinate system of the other. In fact, it was found preferable to rotate *both* the instrumental and target polarizations to a position angle of 0° at 8 μm. This then puts all (or most of) the instrumental polarization in Q and all (or most of) the source polarization in U (see Fig. 2 for an example).

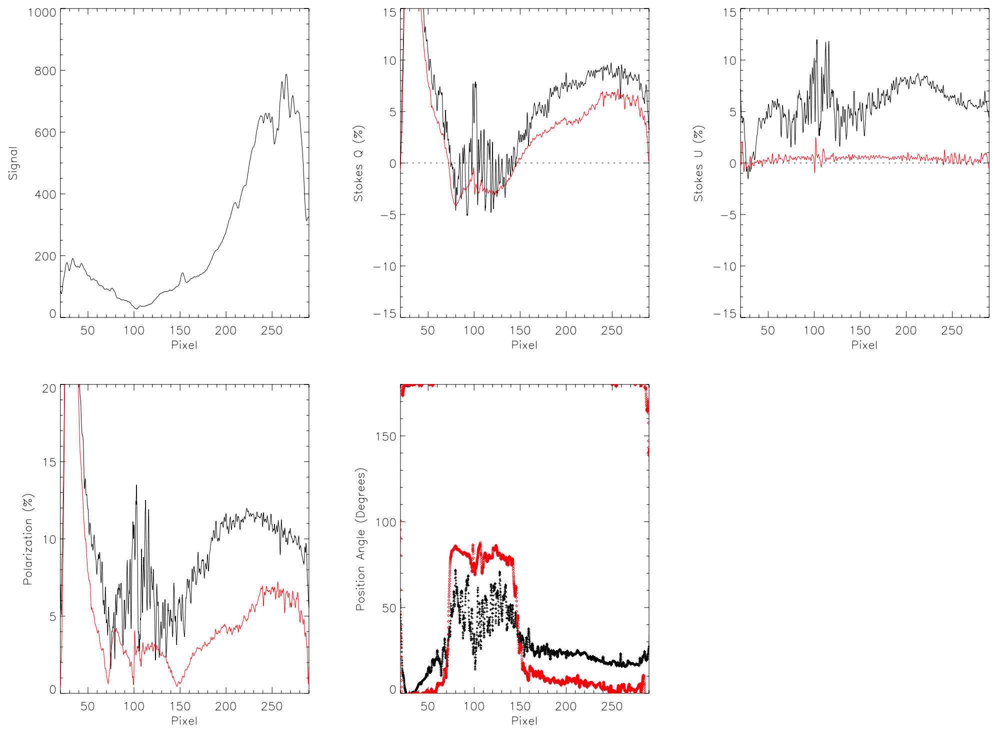

Figure 2. Uncorrected polarization spectrum of the deeply embedded Young Stellar Object RCW57 IRS1. The instrumental polarization is shown in red. The data between about pixels 75 and 125 is severely affected by telluric ozone absorption.

In this way at least one Stokes parameter (U in this case) is essentially clean of instrumental polarization, and so can be reliably assessed (and/or modelled) for the presence of trace mineralogical features. But the other Stokes parameter (in this case Q) of the science target can be corrected by a simple subtraction of the observed and instrumental Stokes parameters. The result of such a subtraction is shown in Fig. 3. Alternatively a 3×3 transformation matrix describing the instrumental polarization as an imperfect polariser can be formed (necessarily ignoring any possible circular polarization component), and subsequently inverted to yield the true source polarization. This is the more rigourously correct approach but in practice it was found that the two methods were very consistent, as expected in the case of small polarizations. In some cases though residual artefacts may remain in the corrected Stokes parameters, especially where the source polarization is only a few percent. Determination of the polarization position angle, typically defined astronomically as east of equatorial north, is more straightforward without these multiple rotations to zero degrees. So a direct subtraction of P_{inst} as observed, along with calibration by an astronomical polarized standard, is performed.

As a final comment on the TIMMI2 instrumental polarization, we also found that the magnitude, form and position angle of P_{inst} in the two negative (i.e. chopped) beams – with chop throw typically 10 arcsec, but up to 30 arcsec – were entirely consistent with that in the positive beam. In other words, apart from some very subtle differences still under study, P_{inst} varied very little with position on the detector array. This very likely rules out that the array itself was in some way polarization sensitive, consistent with the advice from the manufacturer.[9]

We now present a science case for construction of a mid-IR polarimeter on an ELT. For want of a better (or more imaginative) name for this instrument we refer to it here as MIDIRP.

3. MAGNETISM AND STAR FORMATION

From a theoretical standpoint it has been recognized for some time now that magnetic fields can regulate star formation, from the beginning of core collapse to the formation of circumstellar disks and bipolar outflows.[13]

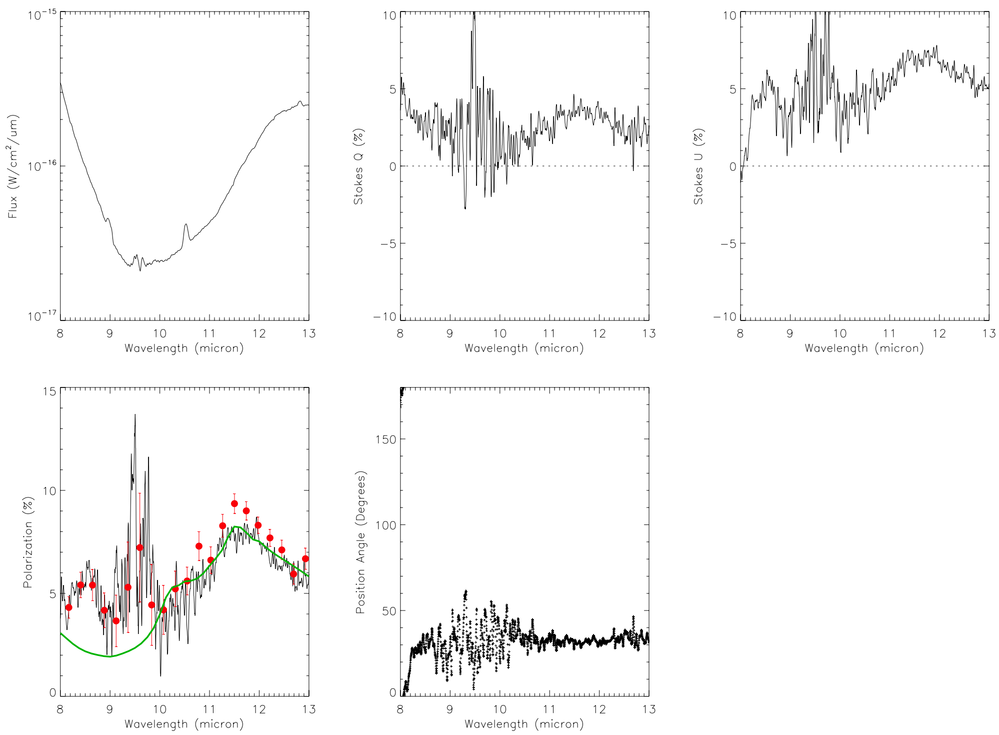

Figure 3. The corrected polarization spectrum of RCW57 IRS1. The data between about 9 and 10 μm is severely affected by telluric ozone absorption. The red data points represent the low resolution spectrum,[4] whilst the green line represents a dust model fit incorporating a mixture of amorphous olivine with a 15% volume fraction of crystalline olivine.[24] The position angle has *not* been referenced to the celestial equatorial co-ordinate system. Note the extremely deep silicate *absorption* band, yet the polarization is observed in *emission*. Emission lines due to [ArIII], [SIV] and [NeII] are seen in the flux spectrum at 9, 10.5 and 12.8 μm from a HII region lying in front of the embedded source.

For instance, depending on the ratio between the field strength and the core mass the pressure provided by the field could support the cloud against gravitational collapse. Such support will remain until some fraction of the field can diffuse out, a process known as ambipolar diffusion occurring within the so-called sub-critical collapse scenario, and which depends on such things as the ion-neutral fraction. At this point the core becomes supercritical and can collapse essentially unimpeded by the field.

Furthermore, subsequent to collapse and the formation of an accretion disk around the forming star, a highly collimated outflow from the polar regions is now seen as a ubiquitous and essential part of the star formation process.[14] It is postulated to be a major factor in extracting angular momentum and allowing accretion to proceed. The most efficient mechanisms for generating bipolar outflow typically invoke magnetic fields embedded within the circumstellar disk. The field acts in concert with rotation to tap the gravitational potential well of the star+disk system to drive material off the disk surface. Further, magnetic fields are also suspected to be the major collimating agent, maintaining the bipolarity over large, parsec-scale distances.

From these perspectives, namely that of initial collapse and subsequent outflow, magnetism may be regarded as an essential element in the formation of stars, and a strong case for observing the magnetic field in star forming regions may be put. Indeed, the two leading candidate hydromagnetic mechanisms for bipolar outflow from disks – namely the centrifugal and magnetic pressure models – predict many similar observable signatures, such as flow rotation. But the predicted magnetic field configurations within the disk and outflow are markedly different. So mid-IR polarization observations may be the best – perhaps only – way to discriminate between the two models. As a measure of the importance placed by astronomers on the role played by magnetic fields in the formation of stars, it is listed as a key question in the topic of the origin and evolution of stars and planets, contained in the document[15,16] "A Science Vision for European Astronomy" by de Zeeuw & Molster.

3.1 Previous observations

The data in Refs. 17 and 18 represented the first attempts at a statistical study of the influence of magnetism on star formation using 8–13 μm mid-IR observations, obtained with the UCLS. These studies involved 22 sources, including 13 embedded YSOs with well defined disk and bipolar outflow axes. In Ref. 19 the total sample size was increased to 28, a result of a few more polarization observations, e.g. at 25 μm with ISOPHOT,[20] but mainly due to additional disk and/or outflow axis determinations from the literature for comparison to pre-existing UCLS data. The sample included 24 objects with a flattened circumstellar structure, be it a disk or envelope or core, and 26 with a signature of bipolar outflow. A review is given of the interpretation of the mid-IR data in terms of cloud collapse and the mechanism of bipolar outflow. This was accomplished by comparing the polarization position angle with the axes of symmetry – i.e. outflows, disks and the Galactic magnetic field – associated with the sample of predominantly massive YSOs. Strong correlations were seen, e.g. in many objects a magnetic field component inferred from absorptive polarization – arising within the cold dusty region – lay in the plane of a flattened disk-like structure, and/or orthogonal to an outflow axis. Also, in several sources where emissive polarization – associated with the warm dusty region – was detected the inferred field component was closely aligned with the outflow. Assuming the field is embedded in the disk – almost certainly the case for the absorptive component, but ambiguous for the emissive component (see below) – these would be toroidal and poloidal magnetic fields respectively. Essentially the magnetic pressure model for outflow predicts a dominant toroidal field in the disk, whilst the centrifugal model predicts a dominant poloidal field. So there remains ambiguity in the current data with respect to its interpretation in the context of hydromagnetic outflow models. Finally, in several instances the relation between the various axes, along with that of the interstellar magnetic field, was consistent with the initial collapse as having proceeded sub-critically.

3.2 Resolving magnetic fields in star forming regions with MIDIRP on an ELT

The results presented in Ref. 19 were derived from single pointed observations in an ~ 5 arcsec aperture with the UCLS or 79 arcsec with ISOPHOT. Clearly imaging observations could advance this field of study by mapping the magnetic field in the very near environs of YSOs. But only a few such observations have been published, specifically those with NIMPOL of Orion BN/KL[21] and G333.6-0.2,[12] objects respectively near the beginning and end phases of the star formation process. These hint at the potential power of such observations to stringently test models for the mechanisms at the heart of star and planet formation. For instance, toward BN/KL the field was traced from being aligned with the outflow to being toroidal in the disk, consistent with the correlations seen in Ref. 19 but seemingly at odds with the latest model predictions of bipolar outflow.[22] In the case of G333.6-0.2 the field took on a roughly hourglass shape centred on a cluster of massive O-stars, once again hinting that the original core was sub-critical.

As previously noted, in the 8–13 μm spectral region both polarized emission and absorption are possible, which can be deconvolved to reveal a change in the magnetic field direction. Four outflow sources are known where this occurs such that the absorptive and emissive components indicate a magnetic field in the disk plane and along the outflow axis respectively.[19] This change in field direction may be due to a line-of-sight twist toward a single polarized source, or the presence of two polarized sources within a spatial scale smaller than the observation resolution element (in these cases about 5 arcsec). For polarizations less than about 10% the two scenarios are indistinguishable, and for the bulk of the observations thus far the distinction has been impossible.

Yet it is extremely important to make this distinction as it has profound implications for the source physics. If the former case is true, then the implication is that the magnetic field changes from being toroidal in the outer disk region to poloidal in the inner disk. This could represent a twist of up to 90° occurring over a scale of perhaps a few hundred to a few thousand or so AU. Precisely how this would occur is uncertain, but probably depends on such things as the disk ionization and rotational dynamics. But if instead the dual polarization arises from extended source structure in the beam, the emissive polarization may probe the field in the outflow itself – perhaps near the base of the outflow but not necessarily in the disk – and so merely suggest that the outflow is being steered into the direction of the ambient magnetic field.

So the data as it stands now appears to suggest that ambipolar diffusion and sub-critical collapse can govern the formation of both low and high mass stars – the latter against what might be expected – and that the magnetic field morphology toward outflow sources is opposite to that predicted by the latest models.[19,22] But the spatial resolution of the mid-IR data thus far has been insufficient to resolve the region at which the outflow likely originates – especially where a disk field might connect with an outflow field – and the number of sources imaged polarimetrically is far too small to make general conclusions.

A polarization capability for MIDIRP on an ELT will dramatically change this situation. It will allow polarization to be detected toward much fainter sources, including those similar in mass to our own Sun. So a comparison of the magnetic field direction with other "axes of symmetry" associated with the detected sources will increase significantly the statistical database with which to study the influence of magnetic fields on star formation – such as discriminating between sub- and supercritical collapse scenarios, and the generation and collimation of bipolar outflows. The $\sim$ 70 milliarcsecond resolution imaging polarimetry capability afforded by MIDIRP can make the distinction between the 'line-of-sight twist' or 'extended structure' scenarios for the magnetic field outlined above. This it will do by directly observing both the disk and outflow fields and the region where they may connect. It is also likely that with higher spatial resolution higher levels of polarization will also be detected, as the field will be less tangled within a single resolution element. Such non-uniformities in the field – and hence in the grain alignment – act to depolarise the emitted or absorbed radiation.

We also note here that, assuming a model like that in Ref. 22, mid-IR polarimetry will easily probe the region of the 'slow' molecular outflow from the disk at radii of tens to hundreds of AU. But it will never probe the origin of fast jets at radii of tenths of AU where dust cannot survive due to the high temperature. Even so, the magnetic field observed at radii of $\sim$ 10 AU will strongly constrain the shape that the field can take interior to this – through the governing physics – and hence still impact on models for jet generation.

A polarization capability for MIDIRP will be complementary to the current and future generations of sub-millimetre polarimeters on facilities such as SMA and ALMA. The mid-IR will probe the magnetic field local to the source(s) of luminosity where the dust temperature is up to several hundred Kelvin – and indeed is the only means of doing so – whilst the submm probes the field throughout the extent of molecular cores where the dust temperature is more like several tens of Kelvin. So the connection between the magnetic field at large and small spatial scales within star formation regions can be established.

4. COSMIC DUST EVOLUTION AND LIFE CYCLE

The life-cycle of cosmic dust, from its creation and ejection by evolved stars, its transport through the interstellar medium (ISM) and molecular clouds, to its deposition into planet-forming disks, is an open and topical area of research. Each environment may have different effects on the nature of the dust, such that the grains undergo structural, chemical and/or morphological changes. For example cosmic ray hits and/or supernova shocks in the diffuse ISM may induce size and structural changes leading to amorphousness. Agglomeration of different components (e.g. silicates, oxides, ices, carbonaceous material) may lead to grain growth in cold, dense molecular clouds and circumstellar disks. And crystallisation may occur in the warm inner regions of disks or outflows. These changes in the dust should also induce spectral changes in the mid-infrared, such that spectroscopy of the dust becomes a diagnostic of the physics occurring at the source. The exploitation of dust features to elucidate such physical processes, especially those associated with forming stars and planets, is a key goal contained in the document "A Science Vision for European Astronomy" by de Zeeuw & Molster.[15,16]

4.1 Previous observations

Within the 8–13 and 16–22 μm mid-infrared atmospheric windows many confirmed or suspected cosmic dust components possess signature resonances. Modelling of observational data in Refs. 23, 24 and 7, using silicate as the primary dust species, shows definitively that the polarization spectrum is much more sensitive – and therefore diagnostic – to the presence of admixtures or mantles of other dust components than is the typically observed extinction spectrum. Furthermore, the silicate species itself, e.g. olivine or pyroxene, and the intrinsic Fe/Mg ratio, can produce a very different polarization spectrum.

Examples of the utility of mid-infrared spectropolarimetry in the investigation of cosmic dust, and the physical processes which determine its properties, are the observations at 10 and 20 μm of the BN Object[25] and the massive

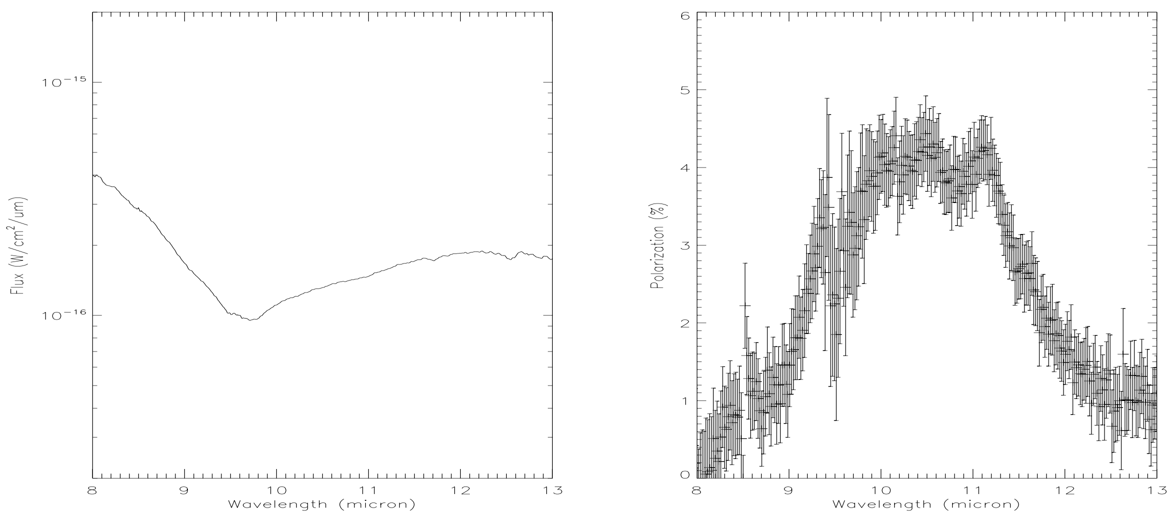

Figure 4. TIMMI2 mid-infrared flux and polarization spectra of the YSO IRAS13481-6124, observed at the ESO 3.6 m telescope in 2006. The broad polarization band is due to amorphous silicate dust, corresponding to the broad absorption band in the flux spectrum. The sharp polarization feature at 11.2 μm is not unambiguously identified, but could be due to crystalline olivine.[23,26] Whatever the particular dust component responsible, the conventional (flux) spectrum gives very little clue to its presence, apart from a very shallow absorption superposed on the deeper amorphous silicate feature.

YSO AFGL 2591.[26] In AFGL 2591 a polarization feature at 11.2 μm was discovered, interpreted as possibly arising from a structured silicate produced during an annealing episode when dust reached a temperature of $\sim$ 1300 K. This observation pre-dated by a decade the 'crystalline silicate revolution' inspired by ISO. Another example is the almost precise match[7,24] between the polarization spectrum of the diffuse ISM and a laboratory amorphous olivine silicate with a Fe/Mg ratio of 1.5. With such a high quality fit, limits could be placed on the abundance of other potential dust components in the ISM – such as crystalline silicate and SiC – plus it could be used as a template to model sources in molecular clouds, where mantle growth and coagulation likely occurs.

4.2 Exploring the cosmic dust life cycle with MIDIRP on an ELT

The past spectroscopic investigations had a resolving power R $\sim$ 40, and data for 55 mainly embedded high mass (high luminosity) sources was published in the spectral atlas of Ref. 4. But higher spectral resolution to search for trace mineralogical components, coupled with enhanced sensitivity to probe more lower mass environments, are needed to significantly advance the field.

For a few years between 2004 and 2006 the mid-infrared spectropolarimeter TIMMI2 on the ESO 3.6 m telescope provided a step in this direction. The full data set from these observations are still being assessed, but already include the first detections of mid-IR polarization toward an Herbig Ae/Be star (R Mon) and an FU Orionis type object (V883 Ori). But perhaps most impressively a sharp polarization feature seen in *absorption* at 11.2 μm was detected toward the sparsely studied embedded YSO IRAS13481-6124 (see Fig. 4). It is very similar to that seen toward AFGL 2591.[26]

This represents only the second detection of the feature, with a $\sim$ 20 year gap between them, despite the observation of $\sim$ 75 sources by the UCLS overs its $\sim$ 10 years of spectropolarimetric operation. This included several targets lying behind large columns of the diffuse and dense ISM, the ultimate source of the dust in these objects. So if the 11.2 μm feature really does arise from crystalline olivine,[26] then this potentially hints at a hitherto unknown processing phase in the life cycle of cosmic dust. For instance, it implies that the annealing episode which must crystallize the dust can happen in a much earlier phase of evolution of the central star than hitherto thought, namely whilst it is still deeply embedded in its natal cocoon. This would be while the star is probably still accreting, before it has dispersed the surrounding material and almost certainly before the formation of planets. The fact that only 2 of about 75 sources show the 11.2 μm polarization feature further implies that either this is a rare event or a short-lived evolutionary phase. Given the almost ubiquity of crystalline silicates seen in *emission* with conventional spectroscopy in later stages of star formation – such as in T Tauri and Herbig Ae/Be stars – it is tempting to favour the latter explanation. Alternatively, the crystalline fraction is much lower in the other sources, only a few percent compared to around 15% for AFGL 2591 and IRAS13481, and hence the decreased line-to-continuum ratio makes its detection that much more difficult.

Whatever the case, the high sensitivity and spectral resolution afforded by MIDIRP will assist in the detection of the 11.2 μm band in more objects. It will be particularly interesting to conduct a census of the band within specific molecular clouds, where low mass stars are forming, as the current detections are toward isolated high mass stars. This will allow a better determination of the uniqueness of the band, and/or when the dust processing is 'switched on', and what properties of the central star or environs influence the feature's formation and detection. In so doing it will be possible to study in detail this potentially unknown phase in the cosmic dust life cycle.

4.2.1 Where will MIDIRP beat a simple spectrometer?

In the era of extremely high sensitivity mid-IR spectra coming out of the IRS on Spitzer, and soon MIRI on the JWST, it is valid to ask the question of why go to the extra effort and expense of equipping an ELT mid-IR instrument with a polarimetry mode (even though the additional resources required would not be that great in the context of building the entire instrument).

The simple answer is that polarimetry can do things that conventional spectroscopy cannot, especially for young, embedded stars. Perhaps most obviously polarization constrains the shape of dust grains. But there are other reasons, which briefly (but not exhaustively) are that polarization i) determines the bulk amorphous silicate mineralogy, ii) detects trace mineralogical structure of dust more easily and uniquely, i.e. the polarization band can be stronger and more diagnostic, iii) allows study of the mineralogy of warm *emitting* dust behind large columns of cold *absorbing* dust, and iv) distinguishes between potential dust morphologies, e.g. mantled versus mixed versus separate populations. These points are explained in more detail below.

The respective strengths of the 10 and 20 μm amorphous silicate bands remains an issue even after $\sim$ 40 years of astronomical mid-IR spectroscopy. Their ratio is diagnostic of the silicate mineralogy, including olivine versus pyroxene and the relative amounts of metals such as iron and magnesium. But conventional spectroscopy of the 20 μm band is particularly sensitive to radiative transfer effects – i.e. competing emission and absorption along a radial temperature gradient – such that in some cases the band can hardly even be discerned in the spectrum. Further, conventional spectroscopy in the 20 μm atmospheric window is particularly difficult due to multiple strong telluric water vapour bands. The observed source spectrum is divided by a standard star spectrum to correct for these features, a process relying on the two observations being done at the same airmass and with stable atmospheric transmission. Polarization is much less influenced by these two effects. For instance, polarization is a self-correcting quantity since it is formed from the quotients Q/I and U/I from the *same* observation. Therefore, polarization is a much better diagnostic of the band ratio, and hence of the silicate species. There are currently only a handful of such 20 μm polarization observations,[4,25,26] but which already show significant differences.

The conventional spectra of AFGL 2591 and IRAS13481-6124 show little that is unusual at 11.2 μm, merely a slight inflection at R $\sim$ 40, resolved into a shallow absorption band within the much deeper 9.7 μm amorphous silicate absorption at R $\sim$ 150 (see Fig. 4). However, this inflection/absorption band is seen with similar properties in almost *all* objects in Ref. 4 and those we have observed with TIMMI2, and could be due to a number of species. Possibilities include water ice, polycyclic aromatic hydrocarbon (PAH), carbonate, SiC or crystalline silicate. Spectropolarimetry is thus the *only* means of clearly revealing and diagnosing the feature. Another example is the relatively low mass YSO SVS13 in NGC 1333. In this case the conventional spectrum shows a double-trough absorption profile, one being due to the usual 9.7 μm silicate, and the other ambiguous but with possibilities as above. The polarization spectrum is so far unique, and identifies the carrier as most likely SiC.[4,23] These examples show that reliable identification of the carriers of some cosmic dust bands in the mid-IR is only possible with polarization data.

Furthermore, as predicted in Ref. 27 mid-IR emissive polarization can be seen even if it is overlain by a high column density of absorbing material, such that the conventional spectrum shows only an absorption band. Several examples are in Ref. 4, but perhaps the best is RCW57 IRS1, now confirmed with TIMMI2 (Fig. **??**).

Modelling of the polarization suggests that the emitting silicate dust is partially crystalline,[24] a finding that would simply be impossible without the polarization data.

As a final testament to the power of mid-IR polarimetry we note that the polarization spectrum modelled with silicate cores and water ice mantles is very different to that where the silicate and ice are mixed. The former case is a somewhat idealised but almost universally accepted structure of dust in molecular clouds. The latter case instead represents a situation where grains grow a mantle first, and then collide and stick with each other so that their structure becomes somewhat fluffy, with some internal voids being filled with ice. Mid-IR polarization data covering the 12 μm water ice librational band can aid in discriminating between these two scenarios, especially if combined with polarization data for the 3.1 μm water ice band. Related to this is whether two dust species exist as separate populations, or again with a core-mantle versus mixture morphology. Such a study was conducted for dust along the path to the Galactic Centre in Ref. 28. Combining mid-IR and 3.4 μm polarization it was concluded that the hydrocarbon carriers of the 3.4 μm band existed separately from the silicate carriers of the 9.7 μm band. This severely challenges – at least for this line-of-sight – the long-standing model which postulates the existence of an organic refractory mantle on silicate cores.

There is thus enormous scope for further mid-infrared spectropolarimetric observations to discover more polarized sources and study the dust life-cycle across the various stellar evolutionary phases. From general considerations, plus the specific examples given above, it is clear that an instrument like MIDIRP on an ELT could make great strides forward in these areas. It is also likely that when weaker targets are observed the polarization will be stronger, since they potentially lie behind a larger column of dust. This has been seen for instance toward the pre-stellar absorbing core HH108 MMS in Ref. 29 using ISOCAM data. More such observations of the type described here are especially needed of stars nearer the mass of the Sun, so that a reliable comparison can be made between the dust debris found in our solar system – such as in comets and meteorites – and that in the envelopes around other stars.

5. POTENTIAL TECHNICAL CHARACTERISTICS OF MIDIRP

Without going into a detailed technical design there are several basic features that our experience dictates should be part of a polarimetry mode for an ELT mid-IR instrument. They will be clear from the body of this document, but are summarised below.

1. The instrument should be capable of observing in both the 8–13 and 16-22 μm atmospheric windows, and ideally also in the 4.8 μm window, in order to cover as many dust resonances as possible. The 10 and 20 μm windows are especially complementary as they overlap with many spectral features from both amorphous and crystalline silicates. A 20 μm capability will also allow polarization, and hence the magnetic field, to be traced to larger spatial scales since it is sensitive to cooler, and hence more extended, dust emission.

2. The instrumental polarization should be kept to a minimum. Our experience with TIMMI2 shows that if the instrumental polarization can be well characterised and is stable then the data are not as seriously degraded as might otherwise be thought. Even so, a large and spectrally complex $P_{\rm inst}$ will likely make reliable detection of small, say $\leq 1\%$, polarizations that much more difficult. For more detail we refer to the considerations given to this issue in Ref. 30.

3. If possible – and CanariCam on the Spanish GTC will soon serve as a test-bed[31] – the Stokes Q and U parameters should be observed simultaneously to decrease, or even eliminate, effects due to atmospheric transmission variation. Given a good mid-IR site this design parameter, requiring a Wollaston prism, may not be absolutely crucial for polarizations greater than a percent or so.

4. For spectroscopy the entire 8–13 and 16–22 μm windows should be covered in a single grating setting at a resolution of ~ 200. This will again decrease the influence of atmospheric transmission variations that would otherwise affect the stitching together of separate spectra.

5. For imaging at least three filters should be available across the 8–13 μm window, spaced such that they cover the full extent of the silicate polarization profile,[3] e.g. 8.5, 10.3 and 12.5 μm. In this way reliable separation of emissive and absorptive components can be achieved.

6. The half-wave plate should be rotated through its entire 360 degrees so that the spectrum is insensitive to the ripple effect of interference between the parallel faces of the plate.[32]

7. Though not previously considered the feasibility of a circular polarimetry mode should also be investigated. Any change in the grain alignment along the line-of-sight should produce circular polarization,[33] offering another opportunity to study magnetic field twisting and/or fractionation of dust properties along the line-of-sight.[34]

6. CONCLUSIONS

Despite astronomical mid-IR polarimetry being almost 40 years old now the potential parameter space has barely been touched. In this paper we have explored the two major issues where mid-IR polarimetry can make unique contributions, especially if utilised on an ELT. These are i) studying the role of magnetic fields in star formation, and the generation and collimation of bipolar outflows from compact astrophysical objects, and ii) revealing the life-cycle of cosmic dust during its journey from its formation to its deposition sites, namely evolved stars and planetary disks. These are key questions outlined in the document[15,16] "A Science Vision for European Astronomy". We can also be confident that the opening up of the discovery space by such a powerful instrument will inevitably lead to new, unexpected and exciting science.

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