Spectropolarimetry of the 3-µm water-ice feature towards young stellar objects

R. P. Holloway, A. Chrysostomou, D. K. Aitken, J. H. Hough and A. McCall

Department of Physical Sciences, University of Hertfordshire, College Lane, Hatfield AL10 9AB

Accepted 2002 June 5. Received 2002 May 27; in original form 2002 March 19

ABSTRACT
We present spectropolarimetry of the 3-µm water-ice feature towards five young stellar objects embedded in molecular clouds, including the Becklin–Neugebauer object, with wavelength range and spectral resolution much improved over previous studies. There is ice-feature polarization excess in four of the five sources and our observations indicate that the polarization is caused by the dichroic absorption of aligned grains in at least three of these. The ice-feature polarization excess is always accompanied by a systematic variation in the position angle of polarization, indicating that the ice-mantled grains are fractionated in the line of sight through a changing magnetic-field orientation. The results are compared with a recently published mid-infrared survey and we find good correlations between the polarization of the 3-µm ice feature and the 10-µm silicate feature, compelling evidence for the presence of water-ice mantled silicate grains, and which suggests that the core/mantle ratio does not differ widely between objects, an important result for grain models.

Key words: techniques: polarimetric – stars: formation – stars: pre-main-sequence – ISM: clouds – dust, extinction – infrared: general.

1 INTRODUCTION
The study of dust grains is an important area in modern astronomy, since their optical properties are required for many astrophysical applications, including the modelling of sources surrounded by or obscured by dust. Despite the considerable observational and theoretical effort by numerous investigators, many of the precise chemical and physical properties of dust remain largely unresolved. It has long been known that dust plays an important role in star formation, and it is becoming increasingly clear that grains make a significant contribution to the chemical evolution of circumstellar environments. In diffuse interstellar clouds, the dominant reactions are gas-phase ion–molecule reactions, but these are less important in the star-forming regions of molecular clouds (Williams & Miller 1993). Gas and dust protects the dense cores of molecular clouds from the UV light of nearby stars, keeping temperatures down to about 10 K, and it is expected that under these conditions even highly-volatile gas molecules will accrete onto cold dust grains forming an ‘icy’ coating. Ammonia and formaldehyde are examples of molecules whose interstellar abundances cannot be explained by gas-phase reactions alone (Galloway & Herbst 1989) and it has been suggested that the icy coatings, or ‘mantles’, are likely to form the substrates for various chemical reactions (Tielens & Hagen 1982).

Observations in the infrared are well suited to the study of the sites of star formation and of the interstellar medium in general. In the near-infrared (NIR), the main spectral features are 3.1-µm H₂O ice, 3.47-µm ‘carbonaceous’ feature (see below) and 3.54-µm CH₃OH ice. This study is primarily concerned with the 3.1-µm feature, which we compare with the main mid-infrared feature — silicate absorption at 9.7 µm. Silicates are found in both absorption and emission in a wide variety of objects, but water ice is not as readily detected. Whittet et al. (1983) were the first to find water ice in a molecular cloud (the Taurus complex) and there is some evidence to support the idea that the ice should be associated with silicate grains, Lee & Draine (1985) having modelled the line-of-sight polarization in the Becklin–Neugebauer object (BN) using a grain mixture that included ice-mantled silicate grains.

Spectropolarimetry in the infrared is especially useful in determining the optical properties of grains populating the lines of sight towards stars lying in or behind dusty envelopes. Provided that the background source is intrinsically unpolarized then the polarization arises because of the dust. In the infrared, two polarization mechanisms are usually assumed. First, dichroic absorption and/or emission by non-spherical aligned dust grains in the line of sight towards the observed star. Secondly, scattering by circumstellar dust grains, observed as reflection nebulae. In the spectral range covering the ice and silicate features the dominant mechanism is dichroism, and the proof of this comes in the form of a characteristic shift between the peak absorption and the peak polarization of a feature (Kobayashi et al. 1980).

There are a number of theories that can be invoked to explain how grains can be aligned, but whatever the mechanism the observed polarization position angle reveals the alignment direction.
of the grains – for reviews on grain alignment see Lazarian (2000) and Roberge (1996). For magnetic alignment of grains, polarimetry can be a useful diagnostic in determining the structure of magnetic fields in these environments provided that sufficient attention is paid to the correct interpretation of the spectra. Solid-state features in the infrared spectrum result from vibrational transitions of the chemical bonds involved and, in general, polarization across a feature is seen to increase above the continuum level. The NIR is usually dominated by absorptive polarization, but towards the mid-infrared (MIR) and beyond, an emissive component becomes progressively more important. In general, the position angle of absorptive polarization is in the direction of the magnetic field, while emissive polarization position angle is orthogonal to it. Across the MIR spectrum the position angle may be seen to change as one component becomes more important than the other, so interpretation of MIR spectropolarimetry requires the separation of absorptive and emissive components, but at 3.1 \( \mu \)m the predominant mechanism is believed to be dichroic absorption. In this case the most simple interpretation of a change in position angle across the feature is that the proportion of ice to other components changes along the line of sight, i.e. that it is fractionated, and that the alignment of the grains also changes along the line of sight.

Previous NIR spectropolarimetry is limited to perhaps 10 young stellar objects (YSOs), usually with limited wavelength coverage and spectral resolution. In this paper we present new 3.1-\( \mu \)m spectropolarimetric results for 5 YSOs. With the recent publication of a mid-infrared spectropolarimetric survey (Smith et al. 2000, hereafter referred to as SWARH) we take the opportunity to compare ice and silicate data for a sample of nine objects (our four new results and four previously-published results) that are common to the SWARH paper.

We are currently developing modelling software that solves the equations of radiative transfer and the Stokes parameters for (dichroic) polarization (absorptive and emissive). This will enable us to model spectropolarimetry using appropriate optical constants for ice and silicate mixtures, and to establish the core/mantle ratio. We intend to present our results in a follow-up paper.

### 2 OBSERVATIONS AND DATA REDUCTION

Spectropolarimetry of five molecular-cloud YSOs (BN, GL 2591, GL 2136, GL 490 and Mon R2 IRS2) are presented from several observing runs (see Table 1 for a summary). The observations were made at the United Kingdom Infrared Telescope (UKIRT) at Mauna Kea, Hawaii, a classical Cassegrain telescope with a 3.8-m primary mirror. The instrument used was the Cooled Grating Spectrometer (CGS4), a 1–5 \( \mu \)m 2D grating spectrometer with a cold Wollaston Prism (located ahead of the spectrographic slit) that splits the beam into e- and o-rays for analysis. Polarimetric capability is provided by the infrared polarimetry module (IRPOL) located upstream of CGS4, consisting of a half-wave plate retarder that rotates the plane of polarization of the incoming radiation.

One polarization state was recorded on each frame, and observations were performed in sets of eight, the first four with the half-wave plate at 0°, 45°, 22.5° and 67.5° (relative to a fixed reference axis on the sky) with the object in one position on the slit, and then repeated with the object moved along the slit. Each frame consists of a spectrum for the o- and e-rays produced by the prism, for the object and sky, enabling sky subtraction to be achieved. A flat-field frame was obtained at each grating position by observing a black-body source internal to CGS4. All the frames were added to give a single set of eight frames. This was reduced to four frames after sky subtraction, one for each of the four wave plate positions. Wavelength calibration was achieved through observations of emission lines from internal arc lamps (argon and xenon). Position angle calibration was achieved by applying a correction determined using BN itself, adopting a position angle of 115° for the K- and L-band continuum from Hough et al. (1996) and references therein. While it is acknowledged that using this method the absolute position angle is only likely to be determined to within a few degrees, it is worth noting that while an error in position angle calibration will affect its absolute value, it will not affect the value of any observed change across the ice feature, since any such error will be constant across the NIR spectrum. Flux calibration was achieved through observations of a standard star, though K-band flux standards were not taken for all of the objects. While the measured errors in flux density are generally quite small, it should be noted that the process of photometric calibration in spectropolarimetry can induce large

### Table 1. UKIRT observations of ice spectropolarimetry.

<table>
<thead>
<tr>
<th>Object</th>
<th>( h \ m \ s )</th>
<th>( \alpha ) (2000)</th>
<th>( \delta ) (2000)</th>
<th>Band</th>
<th>Date</th>
<th>Beam (arcsec)</th>
<th>Flux std</th>
</tr>
</thead>
<tbody>
<tr>
<td>BN 05 35 14.2</td>
<td>−05 22 23</td>
<td></td>
<td></td>
<td></td>
<td>15 09 1995</td>
<td>3.05</td>
<td>BS1826</td>
</tr>
<tr>
<td>K 15 09 1995</td>
<td>3.05</td>
<td>BS1826</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L 15 09 1995</td>
<td>3.66</td>
<td>BS1826</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mon R2 IRS2 06 07 45.7</td>
<td>−06 23 23</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K 05 11 1995</td>
<td>3.66</td>
<td>None</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L1 06 11 1995</td>
<td>3.05</td>
<td>BS2210</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L2 06 11 1995</td>
<td>3.66</td>
<td>BS2210</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GL 490 03 27 38.4</td>
<td>+58 47 04</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H 05 11 1995</td>
<td>3.05</td>
<td>None</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K 05 11 1995</td>
<td>3.05</td>
<td>None</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L1 06 11 1995</td>
<td>3.66</td>
<td>BS1590</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L2 06 11 1995</td>
<td>4.27</td>
<td>BS1590</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GL 2136 18 22 29.1</td>
<td>−13 29 46</td>
<td></td>
<td></td>
<td></td>
<td>02 06 1996</td>
<td>1.83</td>
<td>None</td>
</tr>
<tr>
<td>K 02 06 1996</td>
<td>1.83</td>
<td>None</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L 02 06 1996</td>
<td>3.05</td>
<td>BS6378</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GL 2591 20 29 24.9</td>
<td>+40 11 20</td>
<td></td>
<td></td>
<td></td>
<td>05 11 1995</td>
<td>3.66</td>
<td>None</td>
</tr>
<tr>
<td>K 05 11 1995</td>
<td>3.66</td>
<td>None</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L 15 09 1995</td>
<td>3.66</td>
<td>BS7924</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
uncertainties. The polarization efficiency is considered to be 100 per cent in the $H$ and $K$ bands, but in the $L$ band a correction has been applied (see the UKIRT web site) using the efficiency function

$$\eta = \sin \left( \frac{\pi \lambda_0}{2 \lambda} \right),$$

where $\lambda_0 = 3.5 \, \mu m$ and $\eta = 1$ at $\lambda = \lambda_0$.

3 RESULTS AND DISCUSSION

Polarization degree and position angle are shown for each of the sources in the figures below. The well-known Serkowski law (Serkowski, Mathewson & Ford 1975) and Wilking law (Wilking et al. 1980; Wilking, Lebofsky & Rieke 1982) have previously been shown to fit molecular-cloud YSO polarization poorly at these

---

Figure 1. BN spectropolarimetry. Plots of flux (upper frames), degrees of polarization (middle frames) and position angle (lower frames) including MIR silicate feature spectropolarimetry from SWARH. Power-law fit ($\beta = 2.04$) to continuum polarization is shown in centre left frame (dashed line).
wavelengths (Hough et al. 1996), but we found good evidence for a power-law fit to the available continuum polarization using $p(\lambda) = c\lambda^{-\beta}$ (where $c$ is a constant for a given line of sight) as first proposed by Martin & Whittet (1990) and previously used in the Hough et al. study to fit BN (using $\beta = 2$). We used a curve-fitting software application of the method described in Beyer (1976) and found good fits for BN using $\beta = 2.04$, GL 490 ($\beta = 1.62$), GL 2136 ($\beta = 2.64$) and GL 2591 ($\beta = 1.92$). The fit for Mon R2 IRS2 ($\beta = 1.78$) is not as good since the polarization rises sharply at shorter wavelengths, presumably due to scattering. These fits are shown as dashed lines in the degree of polarization plots.

An increase in polarization across the ice feature is clearly seen in all the objects except GL 2591 and for these objects we calculated the polarization excess ($\delta P$), the increase in polarization above continuum levels across the ice feature. Often this is calculated by simply subtracting the power-law continuum from the observed polarization curve, but such simple treatment can give misleading results as polarization must be treated as a vector quantity. We therefore adopt the more rigorous approach of extracting the Stokes $q$ and $u$ parameters as observed at 3.1 $\mu$m and also for the continuum (where $q = Q/I$, $u = U/I$ and $p = P/I$), using the formulae $q = p \cos(2\theta)$, $u = p \sin(2\theta)$.

Figure 2. Comparison of polarization excess (solid line) and excess optical depth (dashed line) in the ice feature. A wavelength shift between peak polarization and optical depth, characteristic of dichroism, is clearly seen in BN (upper-left frame), Mon R2 IRS2 (upper right) and GL 490 (lower left), but is absent in GL 2136 (lower-right).

Since all polarizations are small, we can subtract $q$ and $u$ (continuum) from $q$ and $u$ (observed) to obtain values for ice feature $q$ and $u$, from which we then calculate ($\delta P$) and the ice position angle ($PA_{\text{ice}}$).

The ‘excess’ optical depth ($\delta \tau$) of the feature was determined by fitting a blackbody curve to the flux continuum where available, or across the short- and long-wavelength wings of the absorption feature where the continuum was either unavailable or very limited.

In the following subsections and figures, we show the degree of polarization and position angle for each of the five objects. Since the SWARH MIR data are of interest, these are also shown in a similar form for comparison.

3.1 BN

BN is a relatively nearby and bright YSO, deeply embedded in the Orion Molecular Cloud, OMC-1, and is one of the best studied of infrared sources in molecular clouds. Infrared polarization in BN was first discovered by Loer, Allen & Dyck (1973). Since then, it has been the subject of numerous infrared polarization studies; Serkowski & Rieke (1973), Kobayashi et al. (1980), Dyck & Lonsdale (1981), Lee & Draine (1985), Aitken, Smith & Roche...
The polarization, position angle and flux spectra are shown in Fig. 1, covering the wavelength range 1.5 μm to 2.6 μm with spectral resolution and extent substantially improved over previous studies, and 2.8 μm to 4.1 μm of quality comparable with the results of Hough et al. (1996). The polarization is seen to increase across the 3.1-μm feature to about 15 per cent, accompanied by a change in position angle of about 4°, consistent with the results of Hough et al. It is worth noting that there is an apparent position angle change in the 10-μm spectrum from SW ARH but this is not considered to be a shift due to the feature, most likely it is due to the presence of a small emissive component. A polarization excess is visible in the long-wavelength wing of the ice feature that corresponds to the 3.47-μm feature discovered spectroscopically by Allamandola et al. (1992) and attributed to carbonaceous material and ‘diamond-like’ structures. This was detected in the Hough et al. study and its presence is now confirmed.

Following the method described above, we estimate the 3.1-μm ice-feature excess polarization (δP) and excess optical depth (δτ) to be 6.2 per cent and 1.9, respectively.

In Fig. 2 we show the polarization excess δP(λ) across the ice feature and the excess optical depth δτ(λ) spectrum. We confirm the 0.05-μm shift between peak optical depth and peak polarization, first observed by Hough et al. (1996). This is an important diagnostic confirming that dichroism is the polarization mechanism (Kobayashi et al. 1980).

Table 2. Mon R2 IRS2 K- and L-band polarimetry (our results in boldface showing K-band average and L-band observed ice feature).

<table>
<thead>
<tr>
<th></th>
<th>K band</th>
<th>L band</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P (per cent)</td>
<td>PA (°)</td>
</tr>
<tr>
<td>δP</td>
<td>12.7 ± 0.4</td>
<td>171.2 ± 0.6</td>
</tr>
<tr>
<td>δτ</td>
<td>11.2</td>
<td>170.5</td>
</tr>
</tbody>
</table>

Table 2. Mon R2 IRS2 K- and L-band polarimetry (our results in boldface showing K-band average and L-band observed ice feature).

Figure 3. Mon R2 IRS2 spectropolarimetry. Plots of degree of polarization (upper frames) and position angle (lower frames) including MIR silicate feature spectropolarimetry from SW ARH. Power-law fit (β = 1.78) to continuum polarization is shown in lower-left frame (dashed line).
3.2 Mon R2 IRS2

Mon R2 IRS2 is a YSO in the Monoceros R2 star-forming region, identified by Aspin & Walther (1990) as the illuminating source of the shell-like nebula, and previously studied in IR imaging polarimetry and spectropolarimetry. We have summarized in Table 2 our K- and L-band results and those from previous studies with which we are in agreement. Our polarization spectra for this object are presented in Fig. 3 alongside MIR SWARH data for comparison. The flux spectrum for the ice feature is shown in Fig. 4 (along with flux spectra for the remaining four objects covered in this study).

As expected for ice absorption, the polarization is seen to increase across the ice feature, accompanied by a change in position angle of $4.5^\circ \pm 1.5^\circ$ (for PA_{cont} = 170.8° ± 0.2°).

Our power-law fit to continuum polarization reveals a pronounced long-wavelength wing, as seen in BN.

Following the method described above, we estimate the ice-feature excess polarization ($\delta P$) and excess optical depth ($\delta \tau$) to be 5.1 per cent and 2.5, respectively. As for BN, we plot the polarization excess $\delta P(\lambda)$ and optical depth $\delta \tau(\lambda)$ across the ice feature (also shown in Fig. 2). Polarization peaks 0.05 µm upwards of peak optical depth, which confirms dichroism as the dominant polarization mechanism in the ice feature. This is an important result and the first time that this evidence has been presented for Mon R2 IRS2.

3.3 GL 490

GL 490 is a typical massive YSO that has been extensively studied since its association with the bipolar CO outflows discovered by Lada & Harvey (1981). To date, polarimetry has been restricted to imaging and narrow-band studies, including separate measurements for a spatially resolved core and halo (Haas, Leinert & Lenzen 1992) and at offsets from the source (Yamashita et al. 1989). We present the first H-, K- and L-band spectropolarimetry for this object in Fig. 5 (ice-feature flux in Fig. 4). Our results (boldface) and those of previous studies are summarized in Table 3.

Our H- and K-band results are in reasonable agreement with previous narrow-band studies, although there is a considerable spread in the sample. We can attribute the small discrepancies to differences in beam sizes, since we can see from the previous studies that measurements change substantially, depending on offset from the source core.

![Figure 4](https://academic.oup.com/mnras/article-abstract/336/2/425/1157598)
The general shape of the polarization spectrum follows the expected gradual increase with decreasing wavelength. Following the method described above we estimate a small increase ($\delta P$) across the 3.1-µm ice feature of 0.9 per cent, which is accompanied by a barely measurable position angle change of about $1^\circ \pm 0.5^\circ$ (for PA$_{cont} = 123.8^\circ \pm 0.1^\circ$). We estimate the excess optical depth ($\delta \tau$) to be 0.18, which as we have shown in Fig. 2, peaks short of peak polarization, indicative of dichroism. This is the first time that dichroism has been demonstrated in the ice feature of GL 490, but given the weakness of the absorption feature and the resulting uncertainty in the optical depth it would be beneficial if this were confirmed in a future study.

3.4 GL 2136

GL 2136 is a compact IR source embedded in a molecular cloud. It is a source of intense H$_2$O maser emission and weak OH emission (Allen et al. 1977). Absorption features at 3.1 µm and 9.7 µm were first reported by Willner et al. (1982) and since then GL 2136 has been studied in spectropolarimetry at both of these wavelengths (Hough et al. 1989; Smith et al. 2000), and IR imaging polarimetry by Minchin et al. (1991).

Table 3. GL 490 H-, K- and L-band polarimetry (our results in boldface showing H- and K-band averages, and L-band observed ice feature).

<table>
<thead>
<tr>
<th></th>
<th>H band</th>
<th>K band</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$P$ (per cent)</td>
<td>$PA$ ($^\circ$)</td>
</tr>
<tr>
<td>$a$</td>
<td>9.7 ± 0.3</td>
<td>124.4 ± 0.5</td>
</tr>
<tr>
<td>$b$</td>
<td>10.7</td>
<td>118</td>
</tr>
<tr>
<td>$c$</td>
<td>10.5</td>
<td>120</td>
</tr>
<tr>
<td>$d$</td>
<td>10</td>
<td>115</td>
</tr>
<tr>
<td>$e$</td>
<td>15</td>
<td>133</td>
</tr>
<tr>
<td>$f$</td>
<td>11</td>
<td>122</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


Figure 5. GL 490 spectropolarimetry. Plots of degree of polarization (upper frames) and position angle (lower frames) including MIR silicate feature spectropolarimetry from SWARH. Power-law fit ($\beta = 1.62$) to continuum polarization is shown in lower-left frame (dashed line).
Our results are shown in Fig. 6 with improved resolution and range on the previous study by Hough et al. (1989). Polarization degree increases to 13.5 ± 0.7 per cent across the ice feature and the position angle changes by some 10° to 39° ± 1°, results that are slightly different from those of Hough et al. (P = 16 per cent, PA = 46°). Measurements in the K band compare to within a few per cent and a few degrees. The long-wavelength wing often seen in the ice-feature polarization spectrum in YSOs appears to be present.

We estimate the 3.1-µm ice-feature excess polarization (δP) and excess optical depth (δτ) to be 6.5 per cent and 3.6, respectively. As with the other objects, we compared optical depth with polarization excess but found no wavelength shift in the peaks of these curves (see Fig. 2), and while dichroism seems probable it remains unconfirmed in this object. It is worth pointing out that while a wavelength shift between peak polarization and peak optical depth proves dichroism, the lack of it does not disprove it since the wavelength shift is also dependent on band strength, crystallinity, and the precise chemistry.

3.5 GL 2591

GL 2591 is a compact IR molecular-cloud source that has been studied over a wide wavelength range. Previous spectropolarimetric studies by Hough et al. (1989), Kobayashi et al. (1980) and Dyck & Lonsdale (1980) all found little or no polarization increase across the 3.1-µm ice feature. Our spectropolarimetry results for this object are presented in Fig. 7 (flux in Fig. 4).

Although we see a clear but weak absorption feature at 3.1 µm, we do not observe any corresponding increase in polarization. We estimate the 3.1-µm ice-feature excess optical depth (δτ) to be 0.6. We note that this source has an unusual 10-µm polarization feature which has been attributed to annealed silicates (Aitken et al. 1988).

3.6 Ice and silicate features compared

If the ice exists as mantles on silicate grains, then a good correlation between the polarization profiles of each of these spectral features would be expected, as previously explored by Aitken (1996). In
The 3-µm water-ice feature

Figure 7. GL 2591 spectropolarimetry. Plots of degree of polarization (upper frames) and position angle (lower frames) including MIR silicate feature spectropolarimetry from SW ARH. Power-law fit ($\beta = 1.92$) to continuum polarization is shown in lower-left frame (dashed line).

In particular, one should expect to see similar polarization position angles (PA) and specific polarization (polarization per optical depth) for each of these objects. (Specific polarization depends on the physical and chemical properties of the grains, the degree of alignment and the angle the alignment direction makes with the plane of the sky. If the ice exists as mantles on the grains that produce the 3-µm continuum – presumably silicate grains – then we might expect that the degree of alignment and the dip angle into the sky would be similar.)

For our new results, MIR spectropolarimetry is also available (SWARH). Four further objects (Elias 29, GL 989, GL 896 and SVS-13) that have been previously studied at 3.1 µm (see Aitken 1996, SWARH).

Table 4. Summary of ice and silicate spectropolarimetry.

<table>
<thead>
<tr>
<th>Object</th>
<th>PA$_{3.1}$</th>
<th>PA$_{cont}$</th>
<th>PA$_{ice}$</th>
<th>P$_{3.1}$</th>
<th>P$_{cont}$</th>
<th>$\delta P$</th>
<th>$\delta \tau$</th>
<th>$\delta P/\delta \tau$</th>
<th>PA$_{9.7}$</th>
<th>$\delta P$</th>
<th>$\delta \tau$</th>
<th>$\delta P/\delta \tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BN</td>
<td>116.5</td>
<td>115</td>
<td>118.7</td>
<td>14.9</td>
<td>8.8</td>
<td>6.1</td>
<td>1.9</td>
<td>3.2</td>
<td>118</td>
<td>12.6</td>
<td>3.2</td>
<td>3.94</td>
</tr>
<tr>
<td>Mon R2 IRS2</td>
<td>166.4</td>
<td>170.8</td>
<td>161.3</td>
<td>10.7</td>
<td>5.8</td>
<td>5.1</td>
<td>2.5</td>
<td>2</td>
<td>169</td>
<td>7.3</td>
<td>3.9</td>
<td>1.87</td>
</tr>
<tr>
<td>GL 490</td>
<td>122.7</td>
<td>123.8</td>
<td>118.8</td>
<td>4.1</td>
<td>3.2</td>
<td>0.9</td>
<td>0.18</td>
<td>5.1</td>
<td>128</td>
<td>2.9</td>
<td>1</td>
<td>2.9</td>
</tr>
<tr>
<td>GL 2136</td>
<td>39.5</td>
<td>29.5</td>
<td>52.1</td>
<td>13.5</td>
<td>6.5</td>
<td>3.6</td>
<td>1.8</td>
<td>4.8</td>
<td>7.1</td>
<td>3.5</td>
<td>2</td>
<td>2.03</td>
</tr>
<tr>
<td>GL 2591</td>
<td>169.8</td>
<td>170.6</td>
<td>169.8</td>
<td>5</td>
<td>5</td>
<td>0</td>
<td>0.6</td>
<td>0</td>
<td>170</td>
<td>5.6</td>
<td>2.8</td>
<td>2</td>
</tr>
<tr>
<td>Elias 29</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>4.4</td>
<td>3</td>
<td>1.4</td>
<td>1.7</td>
<td>0.8</td>
<td>15</td>
<td>3.3</td>
<td>1.6</td>
<td>2.06</td>
</tr>
<tr>
<td>GL 896</td>
<td>110</td>
<td>155</td>
<td>89.4</td>
<td>4</td>
<td>3.5</td>
<td>5.3</td>
<td>1.5</td>
<td>3.5</td>
<td>28</td>
<td>5.9</td>
<td>3.8</td>
<td>1.55</td>
</tr>
<tr>
<td>SVS-13</td>
<td>53</td>
<td>56</td>
<td>44.4</td>
<td>6</td>
<td>4.5</td>
<td>1.6</td>
<td>0.5</td>
<td>3.2</td>
<td>50</td>
<td>2.4–5</td>
<td>1.3–3.85</td>
<td>1.3–1.85</td>
</tr>
<tr>
<td>GL 989</td>
<td>124</td>
<td>125</td>
<td>122</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1.2</td>
<td>0.8</td>
<td>110</td>
<td>2.5</td>
<td>0.8</td>
<td>3.13</td>
</tr>
</tbody>
</table>

SWARH. Ice data for these objects from Aitken (1996) and references therein.
and references therein) are also common to the SWARH survey. We can therefore make some interesting comparisons between ice and silicate polarization in a sample of nine YSOs. The whole data sample is summarized in Table 4.

Fig. 8 represents a comparison of the ice and silicate polarizations. In the upper-left frame we compare position angles. Immediately one can see a strong correlation in the position angles with one outlier, GL 896. However, the position angle spectrum for this object is most unusual as it has a very large shift across the ice feature of about 50$^\circ$. Chrysostomou et al. (1996) suggest that its environment is atypical. With this object included, the correlation is very strong (correlation coefficient = 0.93), which, given our sample size, is significant at the 3 per cent level (calculated using the Student's t-test), i.e. there is a 3 per cent probability of the correlation arising by chance. If omitted, the correlation would be almost perfect (0.99) — significant at a level of less than 1 per cent. It may be that GL 896 really is different from the other objects — perhaps the ice exists as discrete grains, or as a mantle on a different component such as graphite — but the difference between ice and silicate position angles is close to 90$^\circ$, which makes us suspicious of the data. More observations are required to confirm the ice, silicate and continuum polarization for GL 896, and while the uncertainty would justify its exclusion, we retain it in the sample but also consider the effect of excluding it.

In Fig. 8 (upper-right frame) we compare the ice and silicate specific polarizations. We use $P/\tau$ as a measure of specific polarization because $P$ is proportional to the difference between optical depths in the directions parallel ($\tau_x$) and orthogonal ($\tau_y$) to the grain alignment direction, as long as this difference is not large. This follows from

$$P = \frac{e^{\tau_x} - e^{\tau_y}}{e^{\tau_x} + e^{\tau_y}} = \tan h \left( \frac{\tau_x - \tau_y}{2} \right) \leq \frac{\tau_x - \tau_y}{2},$$

and, since $\tau_x - \tau_y$ is a small fraction of $\tau_x$ ($\tau_x - \tau_y)/2$ is always small enough for $P/\tau$ to be a good measure of specific polarization.

At first sight, the correlation is poor (0.37) — significant only at a level of 33 per cent — but, with GL 896 omitted, the correlation is greatly improved — to 0.57 (14 per cent) — and, while this is perhaps more convincing, we might have expected an even better result here. This may be due to the failure of our hypothesis that the ice is a mantle on silicate grains, but we would argue that it is due to uncertainties in the silicate optical depths (worst case ±0.8) arising from
the largely-unknown underlying spectrum, which often includes a component from silicate emission. This stance is supported by the poor correlation of ice and silicate $\delta \tau$ (0.65 and significant at 6 per cent) compared with $\delta P$ (0.74 and significant at 2 per cent). (As expected, omitting GL 896 slightly improves these correlations – 0.71 at 5 per cent for $\delta \tau$, and 0.78 at 2 per cent for $\delta P$.) The scatter in $\delta P$ is partly due to observational errors (worst case $\pm 0.5$ per cent) but there is likely to be an intrinsic scatter arising from real differences in the ice and silicate properties. We have not attempted to consider these errors in calculating the correlation coefficients.

The strong correlation between the polarizations is a significant result suggesting that the core/mantle ratio does not differ widely between objects. This has important implications for grain models since it should allow at least one more ‘free’ parameter to be tied down. In summary, we find the correlation between the features to be quite compelling – clearly indicating that the ice is associated with the silicate grains, the first time that this has been unambiguously demonstrated.

4 CONCLUSIONS

We have presented new NIR spectropolarimetry of five molecular-cloud YSOs, including the 3.1-µm water-ice feature. The main findings are as follows.

(i) The usually assumed dichroic nature of the polarization is confirmed in BN, and is now shown for the first time in Mon R2 IRS2 and GL 490.

(ii) We have found polarization excesses in four of our five objects at 3.1 µm, and the excess is always accompanied by a position angle change indicating that the ice is fractionated in the lines of sight and that there is a twist in the magnetic-field direction.

(iii) The ice-feature polarization excess always exhibits a broadened long-wavelength wing in our sample, suggesting that this may be a common feature.

(iv) We confirm the presence of excess polarization in the long-wavelength wing of the ice feature in BN at 3.47 µm, usually attributed to diamond-like structures.

(v) There is a strong correlation between the ice and silicate polarization, which we interpret as evidence for the presence of water-ice-mantled silicate grains. This implies that the core/mantle ratio does not differ widely between objects.

ACKNOWLEDGMENTS

The United Kingdom Infrared Telescope is operated by the Joint Astronomy Centre on behalf of the UK Particle Physics and Astronomy Research Council. We thank the Department of Physical Sciences, University of Hertfordshire for providing IRPOL2 on UKIRT. RPH wishes to thank Dave Alexander (formerly of UH) for some helpful advice on CGS4 data reduction.

REFERENCES


Beyer W. H., 1976, Standard Mathematical Tables. CRC Press, Cleveland


Dyck H. M., Lonsdale C. J., 1979, Astron. J. 84, 1339


This paper has been typeset from a TeX/\LaTeX file prepared by the author.