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10 and 20 μm spectropolarimetry of the BN object

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Summary. Spectropolarimetric observations of the BN object at 10 and 20 μm reveal a surprisingly large ratio of 20 to 10 μm polarization in the respective peaks. The results are compared with the predictions of core/mantle grain models based on graphite and ice mixtures with a variety of silicates. Except for a glassy bronzite, in which the wavelength match to the peak in the 20 μm region is very poor, all of these predict substantially smaller amounts of 20 μm polarization than is observed.

It seems that either the astronomically important silicates have a particularly strong Si–O bending mode, or that the presence of impurities in ice mantles introduces large 20 μm polarization.

1 Introduction

Infrared spectroscopy and spectropolarimetry of obscured sources provide information on the chemical and physical nature of dust grains in the diffuse interstellar medium and molecular clouds. In particular the Si–O bond has spectral structure in the 10 and 20 μm regions and studies of the wavelength dependence of intensity and polarization can constrain the type and physical state of the silicate material, the range of grain-size and shape, and the extent to which other constituents are present either separately or as core/mantle grains.

Studies of extinction at infrared wavelengths rely strongly on heavily reddened sources in molecular clouds and one of the most thoroughly studied of these is the Becklin–Neugebauer Object (BN) in Orion, a relatively nearby and bright Young Stellar Object, deeply embedded within its parent molecular cloud. Published infrared spectroscopy of BN exists from 1–38 μm (Gillett & Forrest 1973; Treffers & Cohen 1974; Aitken *et al.* 1981; Forrest & Soifer 1976; Forrest, Houck & Reid 1976) and spectropolarimetry from 1–13 μm (e.g. Capps, Gillett & Knacke 1978; Dyck & Lonsdale 1981; Aitken *et al.* 1985), but in the 20 μm region so far only broad-band polarimetry has been available. To date, published 20 μm spectropolarimetry exists of only one astronomical source, the heavily obscured and luminous bipolar object AFGL 2591 (Aitken *et al.* 1988).

The available spectroscopic and spectropolarimetric data have been used by Draine & Lee (1984) and Lee & Draine (1985) to derive and assess a model of molecular cloud grains in

OMC-1 along the line-of-sight to BN. Here the dielectric function of 'interstellar silicate' is chosen to match a variety of spectral data, including some pertaining to the diffuse interstellar medium and circumstellar shells around oxygen-rich stars rather than molecular clouds. The 20 μm region seems particularly bereft of unambiguous data relating to molecular cloud extinction; while many spectra of molecular cloud sources are presented in the LRS catalogue (*IRAS* Science team 1986), the interpretation of these is confused by the uncertain roles of emission and absorption. Similarly there are problems in disentangling temperature effects from the 20 μm Trapezium spectra of Forrest & Soifer (1976) and Forrest *et al.* (1976). Spectropolarimetry can often be of assistance in unravelling this complexity since polarization is independent of the form of the underlying emission, so long as this is unpolarized. The latter condition seems to be satisfied, in the mid-infrared, by neutral sources in molecular clouds; in any case the presence of polarized emission is likely to be betrayed by a wavelength dependence of position angle. For BN, spectropolarimetry from 1–13 μm reveals polarized absorption features due to aligned grains containing ice and silicate materials at a virtually constant position angle. These data are fairly well represented by the grain model of Lee & Draine (1985). As an independent test of their model we present spectropolarimetry of the BN object in the 16–22 μm range.

2 Observations and results

The observations were made using the UCL array spectropolarimeter on the UKIRT during 1987 September, with procedures which were similar to those used for spectropolarimetry at 10 μm, and which have been discussed in more detail elsewhere (e.g. Aitken *et al.* 1985). For work at 20 μm a CdSe half-wave plate was used. Its efficiency was 98 per cent at 19.5 μm falling to 75 per cent at 16.5 μm and 87 per cent at 22 μm as determined from measurements with an efficient wire grid; the polarization spectra have been corrected for these effects. The position angle zero for the 20 μm region was determined from sky emission measurements through a wire grid on axis, and is considered to have an absolute uncertainty of $\pm 3°$. Because of high atmospheric background emission at 20 μm the system sensitivity was significantly reduced compared with work at 10 μm.

Fig. 1 shows the wavelength dependence of intensity, percentage polarization and position angle from 8–13 μm and 16–22 μm. The 8–13 μm region data are a composite from a number of runs on different telescopes at different times, including this run, and used beam sizes in the range 4.2–5.6 arcsec. For the 20 μm region the beam size was 5.6 arcsec and two different beam throws of 67 and 24 arcsec E–W yielded essentially identical results. In all cases the beam throw was of sufficient extent to avoid reference beam contamination with parts of the BNKL complex as displayed in the 20 μm maps of Downes *et al.* (1981).

The intensity spectra in Fig. 1 have been corrected for telluric transparency, and flux calibrated by reference to nearby stars: β Peg and α Tau were used at 10 and 20 μm, respectively. During the present run a small wavelength shift between observations of the source and standard sometimes occurred. This was of no consequence so far as the 10 μm spectrum is concerned, but close to the deep telluric features in the 20 μm region the correction has been poor; these points have been omitted from the intensity spectrum in Fig. 1. This slight mismatch has no systematic effect on either the polarization or the position angle spectra, and merely increases the errors of observation.

Inspection of Fig. 1 shows the familiar absorption feature in the 10 μm region with polarization peak shifted to a significantly longer wavelength than the absorption minimum, thus confirming dichroic absorption by aligned grains as the scattering mechanism, as pointed out by Dyck & Beichman (1974). In the 20 μm region there is little sign of an absorption feature in

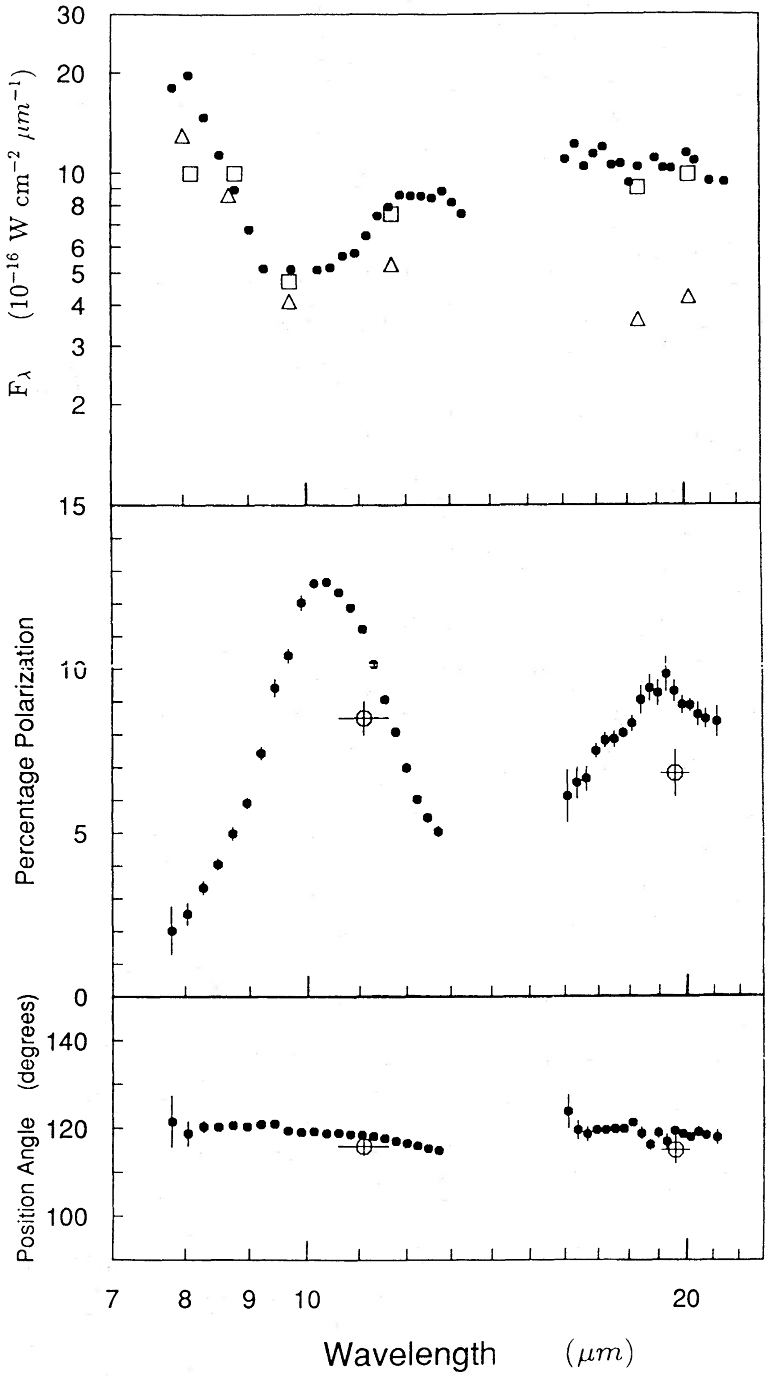

Figure 1. 8–13 and 16–22 μm intensity, polarization and position angle spectra of the BN object. The 10 μm results are a composite from data obtained at various times with beam sizes in the range 4.2–5.6 arcsec; at 20 μm the results refer to a 5.6 arcsec beam. Open triangles and squares show the narrow band photometry of Downes *et al.* (1981) in 2 and 4 arcsec beams respectively, while open circles (bars denote statistical errors and waveband range) are the polarimetric observations of Knacke & Capps (1979) using a 10.8 arcsec beam.

the intensity spectrum, although weak absorption seems to be apparent in the spectra of Forrest & Soifer (1976) and Forrest *et al.* (1976), taken in much larger apertures. The 20 μm polarization, however, shows a clear peak reaching almost 10 per cent close to 19.2 μm, with a constant position angle which agrees with that at 10 μm within the uncertainties of calibration.

We attribute this large 20 μm polarization peak to the O–Si–O bending mode in aligned silicate grains.

It seems that there is a significant contribution to the intensity spectrum of Fig. 1 from diffuse emission close to BN in the 20 μm region. For comparison photometric points with beam sizes of 2 and 4 arcsec from Downes *et al.* (1981) are shown. In our larger beam the diffuse component is negligible at wavelengths less than 10 μm but is significant at 13 μm, amounting to perhaps 30 per cent of the flux, and in the 20 μm region the diffuse component contributes more than 50 per cent of the total flux. This almost certainly affects the shape and depth of any absorption feature and may account for its near absence in this and many other sources at 20 μm. Incidentally, this re-emphasizes the interpretational problems associated with spectroscopy which were touched upon in the introduction.

Nevertheless we believe that the contribution of the 20 μm diffuse component to the polarimetry is small or negligible for the following reasons. (1) The ratio of peak polarization at 20 μm to that at 10 μm is much larger than expected from the 'astronomical silicate' of Lee & Draine (1985), or from the published dielectric functions of any likely silicate material, as is discussed later, and is also much greater than observed in AFGL 2591 (Aitken *et al.* 1988). Emission and absorption from similarly aligned grains yield orthogonal polarizations, so a reduced polarization peak would normally be expected from a polarized diffuse region having similar alignment. (2) Only in the unlikely event of orthogonal alignment directions of the emitting and absorbing grains would an enhancement of polarization be expected and here the polarization peak would be shifted to longer wavelengths, because polarized emission is normally depressed on the short wavelength side of a resonance. Also, and as discussed later, the observed peak at 19.2 μm matches well that of the 'astronomical silicate' but most other materials have polarization peaks at longer wavelenths. (3) There is no indication of any position angle variation in the 20 μm region and this position angle agrees, within calibration uncertainties, with that at 10 μm. (4) While mid-infrared polarized emission is often observed, and is expected, from compact ionized regions (Aitken *et al.* 1986, and in preparation) it has never to our knowledge been seen in dense neutral regions. Finally, Knacke & Capps (1979) find the polarization in a 10.8 arcsec beam at 11.1 and 19.6 μm to be 8.4 ± 0.5 and 6.8 ± 0.7 per cent, respectively, suggesting that in this much larger beam there may be dilution by an unpolarized diffuse component. These results are included in Fig. 1.

These arguments do not rule out a polarized contribution from the diffuse emission but make it seem extremely unlikely. While it is clearly important to repeat the observations in smaller beams, until these become available we will proceed on the assumption that the diffuse emission makes no contribution to the polarization.

3 Discussion

First we wish to draw attention to the quite substantial differences between the polarization spectra of AFGL 2591 and BN (Aitken *et al.* 1988; Dyck & Lonsdale 1981; Kobayashi *et al.* 1980). AFGL 2591 shows no polarization of the ice band absorption feature near 3.1 μm, whereas it is highly polarized in BN. It has an unusually structured 8–13 μm polarization shape compared with BN and other molecular cloud sources, in that there is a marked deficit between 8 and 9 μm, and an additional narrow polarization peak near 11.3 μm. It is now seen to have the substantially smaller 20/10 μm peak polarization ratio of 0.45 compared with 0.76 for BN. AFGL 2591 also has a smaller ratio of $(p/\tau)_{10\,\mu\mathrm{m}}$ by a factor of 2, which reflects the alignment projected along the line-of-sight to the sources. Aitken *et al.* (1988) have argued that AFGL 2591 contains a contribution from unusual grains, possibly more structured silicates, and we therefore consider that these observations of BN are more representative of ordinary molecular cloud material.

Lee & Draine (1985) have modelled the grains in the line-of-sight to the BN object in terms of a population of bare silicate and graphite grains, together with mantles of an 'astronomical ice' on graphite and silicate cores. The icy material is synthesized from laboratory studies of amorphous ice (Léger *et al.* 1979), from which the librational resonance near 12 μm has been removed, and modifications introduced to allow for admixture of NH_3. Oblate rather than prolate grains were found to give a better fit to the wavelength of the 10 μm polarization peak of BN, in that prolate grains shift the peak too much to longer wavelengths; this was noted both by Lee & Draine (1985) and Hildebrand (1988). The model accounts moderately well for the observed spectrum and the linear and circular polarization observed to BN in the wavelength range 2–13 μm.

Extension of the polarimetry to the 20 μm region allows further comparison with likely candidate grain materials and especially the silicate component. Fig. 2a compares bare oblate and prolate 'astronomical silicate' grains of axial ratio 2 with the observed polarization; the peak heights in the 10 μm region have been normalized to 12.5 per cent. It can be seen that the 10 μm preference for oblate grains is demonstrated in the 20 μm region as well, in so much as the peak wavelength position is concerned, although prolate grains give a better ratio of the 20:10 μm polarization ratio. The match of the 'astronomical silicate' to the observed peak positions is good, but there is a marked deficit between 8 and 9 μm, and a serious underestimate of the amount of 20 μm polarization.

We have made a simplified extension of the Lee & Draine (1985) model through the 20 μm region, using their tabulated dielectric properties of 'astronomical silicate' (Draine 1985), a smooth graphite dielectric function made up of a linear combination of *c*-axes parallel and normal to the electric vector in the ratio 1:2 (Draine 1985), and their 'astronomical ice' (Lee & Draine 1985) extrapolated with constant properties from 14 to 23 μm. The proportions of polarization provided by these materials, in the form of bare grains of silicate and graphite, and icy mantles on silicate and graphite cores, are the same as their model B in which the graphite/silicate ratio was 0.45 for both the bare and core/mantle grains. The cross-sections of bare and core mantle/grains have been calculated in the Rayleigh approximation (e.g. Lee & Draine 1985) with oblate grain cores of axial ratio 2 and confocal grain mantles with equal mantle and core volumes. The predicted polarizations have been normalized to 12.5 per cent at the 10 μm peak.

The result is shown in Fig. 2b. The polarization in the 20 μm region remains much less than observed, and the inclusion of icy mantles has shifted the 20 μm peak position to slightly longer wavelengths. Increasing the mantle volume on the silicate grains increases the 20 μm polarization slightly but the 20 μm peak position is also further shifted and becomes inconsistent with observations. Graphite has little effect in this wavelength region.

A similar treatment is also shown in Fig. 2b where the pure amorphous ice of Léger *et al.* (1979) has been used, with the 12 μm librational feature retained. This has introduced a small shoulder in the 10 μm region but leaves the 20 μm polarization peak almost unchanged, while shifting it to a slightly longer wavelength. Increasing the mantle volume has similar effects to the 'astronomical ice' at 20 μm and the shoulder near 12 μm becomes inconsistent with observations. Moving all the icy material from the silicate to the graphite cores slightly improves the fit to the 8–9 μm region, moves the 20 μm peak closer to that observed, but still leaves the 20 μm polarization deficit (Fig. 2b).

The 12 μm H_2O librational ice feature has been observed only on very rare occasions (Gillett & Soifer 1976; Roche & Aitken 1984; de Muizon, D'Hendecourt & Perrier 1986) when it has been attributed to the presence of crystalline ice or to unusually pure amorphous ice. Its more frequent absence may be due to admixtures with other materials which cause a substantial shift to longer wavelengths. It may be that some such effect can account for the high amounts of 20 μm polarization observed, and certainly the lack of ice band polarization in

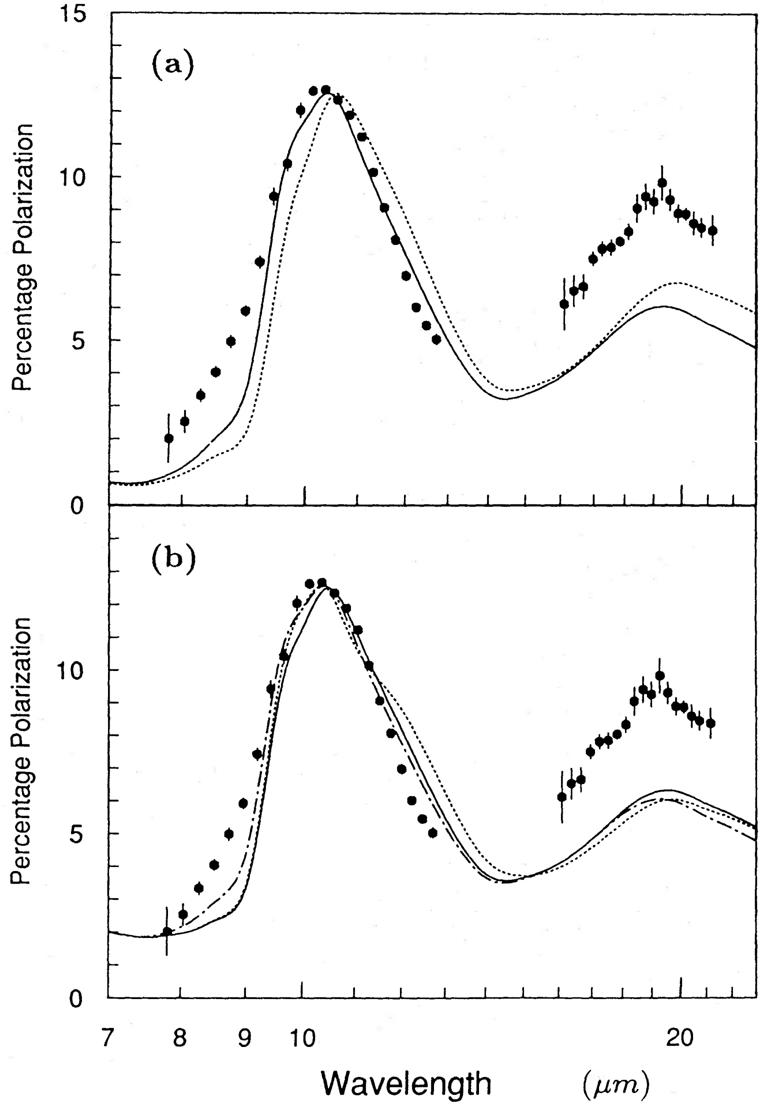

Figure 2. (a) Comparison of the observed polarization with that expected from small, bare spheroidal grains of Lee & Draine's 'astronomical silicate' (1985). Oblate (solid) and prolate (dots) grains of axial ratio 2 are shown and both peak heights in the 10 μm region have been normalized to 12.5 per cent. (b) The same data compared with: (i) (solid) the predictions of a simplified version of Lee & Draine's (1985) model for a mixture of 'astronomical silicate' and graphite core and core/mantle grains, with 'astronomical ice' in which the librational 12 μm feature is suppressed (see text). The volume ratio mantle/core = 1; (ii) (dots) the same but retaining the librational feature (Leger *et al.* 1979); (iii) as (i) (dot-dash) but with bare silicate grains and all the ice as mantles on graphite.

AFGL 2591 (which has a much lower ratio of 20–10 μm polarization) is one of the more striking differences between it and BN. However, at present there is an apparent lack of any laboratory measurements of the optical constants of 'dirty' ices.

The polarization expected from other silicate materials has also been investigated. Optical data on these have been taken from a number of sources: amorphous olivine and enstatite (Day 1979), disordered olivine (Kratschmer & Huffman 1979), and glassy bronzite (Dorschner *et al.* 1988). These 10 and 20 μm profiles are compared in Fig. 3 with the observations. The proportions of graphite and 'astronomical ice' have been kept the same as in the above treatment. No attempt has been made to search through parameter space for a 'best fit'; rather the inten-

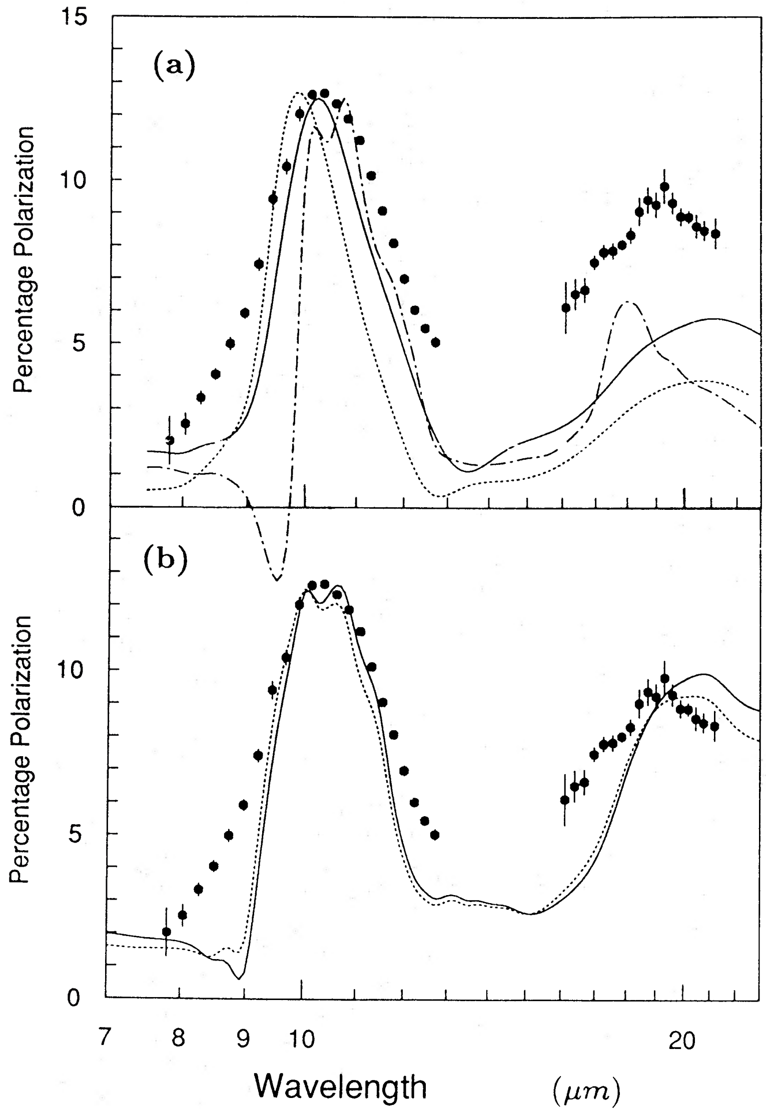

Figure 3. Core and core/mantle mixture as in Fig. 2 (a) but with 'astronomical silicate' replaced by: (a) amorphous olivine (solid) from Day (1979), amorphous enstatite (dots) also from Day, disordered olivine (dot–dash) from Kratschmer & Huffman (1979), and, (b) (solid) glassy bronzite and (dots) the same but with mantles only on graphite. Bronzite is taken from Dorschner *et al.* (1988).

tion is merely to show the qualitative differences between the model and observed polarizations. It is seen that all the materials except glassy bronzite fall short of the large observed 20 μm polarization, and in this case its peak is at a significantly longer wavelength from that observed. Only the 'astronomical silicate' gives a reasonable match to the observed width of the 10 μm feature, which of course it is constrained to do by its construction. The essential result of this modelling is that none of the optical constants provides an adequate fit to either the ratio of peak polarization at 10 and 20 μm or to the details of the 8–9 μm polarization.

The difficulty of reconciling the observed 20 μm BN polarization with the 'astronomical silicate' or any of the likely laboratory studies, while at the same time the observations of AFGL 2591 fit the broader aspects of these quite well, tempts one to reconsider whether BN is anomalous in some respect, and if after all AFGL 2591 is more 'normal' in its polarization properties. Apart from the absence of optical constants of impure mantle materials, the chief point of uncertainty is, of course, the diffuse emission contribution, and while we have argued that this is unlikely to produce effects in the sense observed, it is clearly important to make observations of BN in much smaller beams, and of the diffuse regions close to it. In the meantime we have compared these results with 10 and 20 μm spectropolarimetry of SgrA IRS1, W51 IRS2, and K3–50 (Aitken *et al.* in preparation). The interpretation of these is not so straightforward, since all involve a combination of emissive and absorptive polarization. Nevertheless in both SgrA and W51 there is a clear preference for the large ratio $p_{20\,\mu\mathrm{m}}/p_{10\,\mu\mathrm{m}}$ observed towards BN. A possible explanation for the low 20 μm polarization in AFGL 2591 would be dilution by orthogonally polarized emission from similarly oriented grains close to the central source.

4 Conclusions

20 μm Spectropolarimetry of BN clearly shows the expected peak due to dichroic absorption by aligned silicate grains, even though the absorption is barely evident in the intensity spectrum. The ratio of 20/10 μm polarization is 0.76, larger than expected from the dielectric functions of most astronomically important silicate materials measured to date in the laboratory, and more than predicted by the 'astronomical silicate' of Lee & Draine (1985). We interpret this as implying that either the 20 μm bending mode in the astronomical silicate is stronger than in most materials studied in the laboratory, or there is enhancement of the polarization by some other constituent, such as perhaps mantles of complex ices. Neither is the 8–9 μm region well reproduced by any of the optical constants available. This too may be a consequence of the presence of mantles of impure ices, especially as it is noted that the polarization spectrum of AFGL 2591 (Aitken *et al.* 1988) is a better match to bare silicates in this region, while it conspicuously lacks ice feature polarization at 3.1 μm.

It appears that spectropolarimetry in the mid infrared can be a more critical test of grain materials and models than spectroscopy, in that: (i) the ambiguities introduced in spectroscopy by the generally unknown form of the underlying spectrum are largely avoided; (ii) spectropolarimetry is sensitive to differences of grain structure and chemistry which are not revealed by spectroscopy, and, (iii) spectropolarimetry is sensitive to the absolute value of the band strength.

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