POLARIMETRY OF INFRARED SOURCES

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1. INTRODUCTION

Polarization at infrared wavelengths has been detected from a number of different objects within the Galaxy. These include young sources associated with molecular clouds and H II regions, cool stars with thick circumstellar shells, bi-polar nebulae, and normal stars suffering interstellar polarization. Typical levels of polarization detected at 2.2 μm are up to 25% for the molecular cloud sources, less than ~5% for the cool stars, around 30% for some bi-polar nebulae and less than ~2% for interstellar polarization. For the latter three types of source the origin of the polarization is basically understood: it results from scattering of stellar radiation off small particles in the surrounding shell or nebula in the cool stars and bi-polar nebulae and by transfer of flux through a foreground medium of aligned dust grains for the interstellar polarization. The phenomenon of large infrared polarization in the young stellar and pre-stellar sources is less well understood, and it is to this problem that we address ourselves in this review.

More than 40 such young molecular cloud sources have now been surveyed in the near-infrared for linear polarization (Capps, 1976; Dyck and Capps, 1978; Kobayashi et al., 1978; Dyck and Lonsdale, 1979). About 30% of the samples show more than 10% polarization at 2.2 μm, and about 50% show more than 5%.

One can immediately discount the possibility that the polarization arises by the normal interstellar mechanism along the line-of-sight from the Sun, because the levels of polarization observed are often much higher than the maximum expected levels of interstellar polarization of ~1-2% at 2.2 μm (Hall, 1958; Wilking et al., 1980). In fact, large variations in the degree of polarization observed among sources within the same molecular cloud complex indicate that the polarization arises in the close vicinity of the infrared source, and not over a long pathlength in the interstellar medium. A good example of this phenomenon is the Orion Molecular Cloud (OMC 1) in which are embedded

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BN (IRS 1) and Hilgeman's source (IRS 2), polarized at 2.2 μm at 17.5% and 10.8% respectively (Dyck and Lonsdale, 1979; Johnson, 1979), though they are separated by only ~0.05 pc in the plane of the sky. The trapezium stars, believed to lie at the front surface of the molecular cloud, are nearly unpolarized by comparison (Hall, 1958). Thus the high polarization of BN and Hilgeman's source must arise in the dense material of OMC 1 itself. Given the large thermal infrared fluxes of the young sources, the polarization can be attributed to processes involving dust grains. Understanding the mechanism of polarization may lead to information about the molecular cloud dust grains and to physical conditions within the cloud.

In the following sections we will review the possibilities that the polarization of the molecular cloud sources is due to (a) an enhanced interstellar mechanism within the dense cloud material, or (b) to scattering off dust grains in a shell or nebula around the young objects. In Section 2 we present detailed polarimetric data which are available for two of these sources, BN and GL 2591, and in Section 3, we discuss the general properties of the whole sample. In Section 4 we discuss the consequences of the conclusions reached in Sections 2 and 3 for the conditions which must exist within the molecular cloud complexes.

2. THE POLARIZATION PROPERTIES OF BN AND GL 2591

The BN source in OMC 1 was the first of its kind to be observed polarimetrically (Loer et al., 1973) and has been extensively studied in the interim. Our most up-to-date understanding of the source is that it is a B0 or B1 star undergoing mass loss (Hall et al., 1978) with a surrounding thick layer of dust which obscures it optically and which radiates the infrared spectrum. GL 2591 is a less well-studied source, with similar observational characteristics to BN. In Figure 1 we present a summary of the available photometric and polarimetric data for BN between 1.6 and 20 μm. The two prominent absorptions in the flux spectrum are the familiar "ice" and "silicate" bands. In addition, there are several noteworthy features associated with the polarization spectra.

a. The linear polarization spectrum exhibits two prominent maxima approximately coincident with the ice and silicate absorptions (Capps, 1976; Capps et al., 1978; Kobayashi et al., 1980). In the vicinity of those bands the polarization tends to be correlated with the absorption optical thickness within the band. Note also that the polarization rises again toward 20 μm (Knacke and Capps, 1979).

b. In the continuum, the linear polarization generally declines with increasing wavelength according to

$$P \propto \lambda^{-2.4}.$$

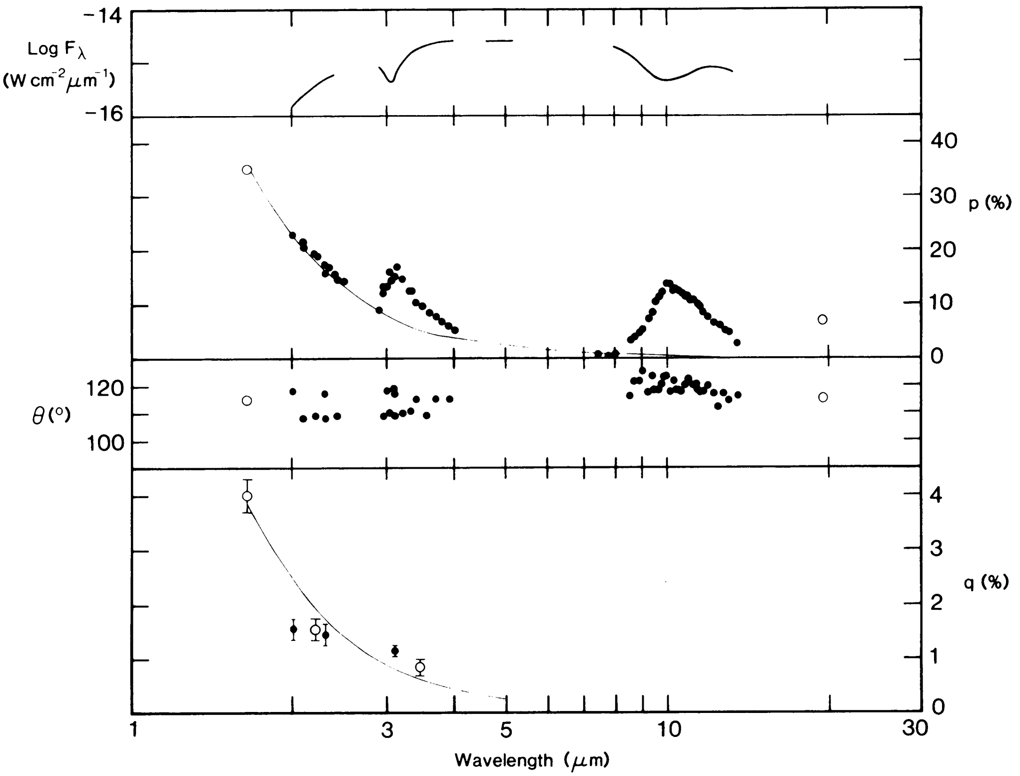

Figure 1 - Linear (p,θ) and circular (q) polarization data for BN taken from Serkowski and Rieke (1973), Capps (1976), Capps et al. (1978), Johnson (1979), Knacke and Capps (1979), and Lonsdale et al. (1980). The open and filled circles represent, respectively, broad- and narrow-band data.

c. The position angle of linear polarization is independent of wavelength between 1.6 and 20 µm, both in the continuum and in the ice and silicate bands (Capps, 1976; Kobayashi et al., 1980).

d. The circular polarization follows approximately the same power law as the linear between 1.6 and 3.5 µm, (Serkowski and Rieke, 1973; Johnson, 1979; Lonsdale et al., 1980). That means that the ellipticity (the ratio of circular to linear polarization) is approximately constant over that range, having a value e = q/p = 9%. There is not sufficient detail near 3 µm to determine the effect of the ice absorption upon the circular polarization.

e. There is no evidence for variability of the linear polarization over nearly a decade. In Figure 2 we have shown data accumulated from 1971 to the present at 2.2 µm. These data were

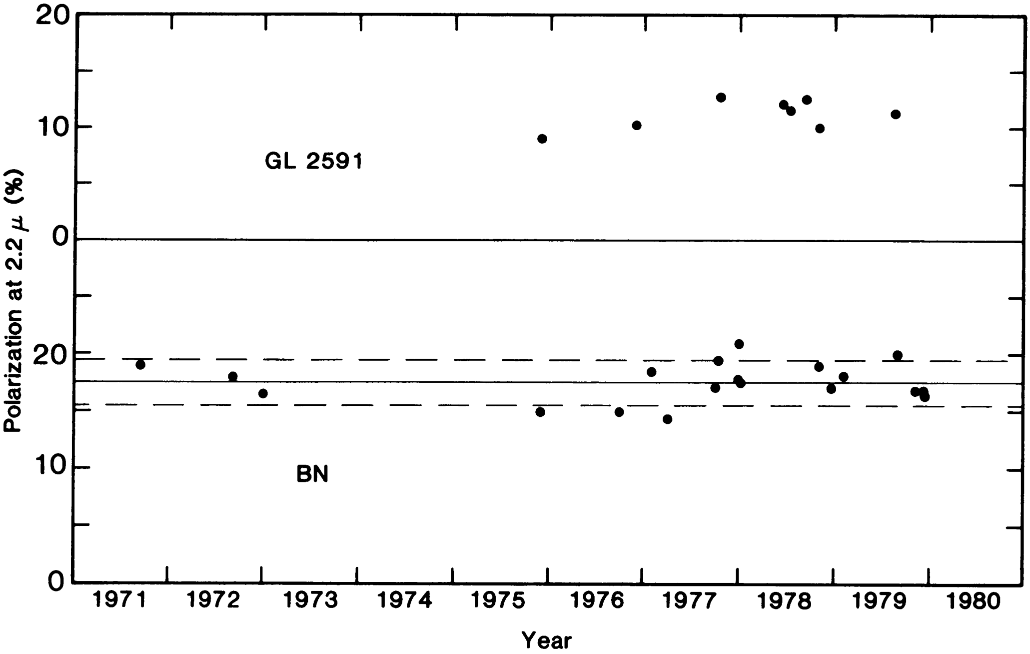

Figure 2 - Linear polarization data for BN and GL 2591 as a function of time. The data were taken from Breger and Hardorp (1973), Loer et al. (1973), Oishi et al. (1976), Johnson (1979), Kobayashi et al. (1978, 1980), and from unpublished observations made at Mauna Kea Observatory.

taken with a variety of instruments, and thus include possible systematic effects. An estimated upper limit to the rms variation in the polarization of P = ±2% is shown by the dashed lines in Figure 2. The average value for the polarization over this time is 17.5%.

f. There is no significant change in the percent polarization as a function of beam size between 5.5 and 40 arcsec evident in data taken at Mauna Kea and that taken by Johnson (1979), Oishi et al. (1976), and Kobayashi et al. (1980).

g. Observations of linear polarization around BN reveal that the surrounding emission is also polarized at 2.2 μm and 20 μm, at a lower level than is BN but with the same angle of polarization (Dyck and Beichman, 1974; Johnson, 1979; Knacke and Capps, 1979). OMC 1/IRS 2 and OMC 2/IRS 3 also have similar position angles of polarization to BN.

h. There is a marginal detection of polarization of 1.6% ± 1% at 71-115 μm at a similar position angle to the shorter wavelength

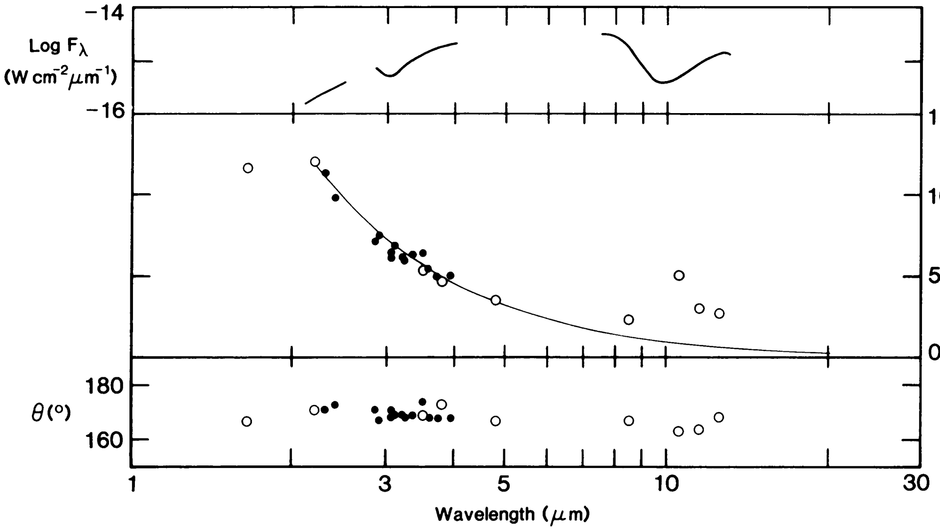

Figure 3 - Linear polarization data for GL 2591 taken from Capps (1976), Dyck and Lonsdale (1980), and Kobayashi et al. (1980). The open and filled circles have the same meaning as Figure 1.

polarization (Gull et al., 1980), in a 1' region centered on the KL nebula.

The flux and linear polarization as a function of wavelength of GL 2591 are shown in Figure 3. There are both noticeable similarities and differences between the data of BN and GL 2591.

a. While the "ice" and "silicate" bands are both evident in the flux spectrum of GL 2591, the polarization correlates positively with optical depth only in the silicate band (Capps, 1976; Kobayashi et al, 1980; Dyck and Lonsdale, 1980). This is in contrast to BN where the polarization increases in the ice band also.

b. The general dependence of polarization upon wavelength in the continuum is less steep than for BN, declining more nearly as

$$P \propto \lambda^{-1.6}.$$

Unlike BN, the continuum polarization does not continue to rise to the shortest wavelengths; a maximum or plateau in the polarization near 2 μm is seen in GL 2591.

c. As in BN there is no dependence of the position angle on wavelength.

d. The circular polarization at 2.2 μm results in a similar ellipticity to that of BN (Lonsdale et al., 1980).

e. The time sequence in Figure 2 shows that there has been no significant variation of the linear polarization between 1975 and 1979.

f. Foy et al. (1979) detected no extended emission around the source; therefore no dependence of the polarization on beam size is expected.

Two models have been proposed to explain the observed polarization of BN. These are (1) transmission of light through a medium of aligned grains (Dyck and Beichman, 1974) and (2) scattering of light by grains in a bi-polar nebula or similar geometrical configuration (Elsässer and Staude, 1978). As explained above, in either case the polarization must arise within the close vicinity of the source. Both models can qualitatively produce the wavelength dependence of the linear polarization between 1.6 and 12 μm for BN. However it is unlikely that the bipolar nebula model is correct for the following reasons. First, Knacke and Capps (1979) have argued that the large observed polarization at 20 μm would require a large scattering optical depth, and hence extraordinarily large dust particles in the nebula. Second, the position angles of polarization for regions surrounding BN should show radial symmetry about BN if it is the source of illumination. Such a pattern is not observed (Johnson, 1979). Third, a dependence of polarization with beam size might be expected if the polarization arose by scattering at some distance from BN, although none is observed. No attempts have been made to reproduce the observed circular polarization with the bi-polar nebula model. The aligned grain model can account for all the observed characteristics of the polarization of BN, including the circular polarization (Lonsdale et al., 1980), the 20 μm polarization and the similar position angles at various locations in Orion. The principal difficulty with this model is understanding the details of the means for achieving the alignment of the grains, and their location within the molecular cloud.

By analogy to BN, the similar polarization properties of GL 2591 can be attributed to an aligned grain model. Dyck and Lonsdale (1980) have been able to account for the lack of polarization in the ice band, while retaining the silicate band polarization, with a model which has a slightly different grain composition mixture than models of BN. Also, the flattening at 2 μm may be attributable to the presence of larger grains than near BN. However, a scattering model cannot be ruled out for GL 2591 from the available data. Since circular polarization from a scattering nebula is sensitive to nebular geometry (White, 1979) the similarity of the ellipticities of BN and GL 2591 speaks for the aligned grain interpretation for GL 2591 also.

3. GENERAL PROPERTIES OF THE ENTIRE SAMPLE OF MOLECULAR CLOUD SOURCES

Linear polarization data at 2.2 μm exist for approximately 40 sources other than BN and GL 2591. Circular polarization measurements exist for approximately 25% of these. Statistical correlations between the polarization of these sources and other observable characteristics may improve our understanding of the polarization mechanism, if it is the same for most of the sources. The sample is strongly biased because polarization measurements are possible only for the brightest among the known observed molecular cloud/H II region infrared sources, whose discovery itself is subject to strong selection effects. However all known cool stars, as evidenced by CO first-overtone bands at 2.3 μm, have been excluded, and it is likely that the majority of the remaining sources are indeed very young objects.

a. Polarization Versus Optical Depth. If the polarization arises by the aligned grain mechanism, then it is possible that it may be statistically correlated with extinction in the foreground material containing the aligned grains. No clear dependence of polarization upon optical depth in either the ice or silicate bands has been demonstrated (Lonsdale, 1980), though there is a tendency for the very highly polarized sources to have deep ice bands (Joyce and Simon, 1979). This result is not surprising since such a correlation could be easily masked by variations in degree and orientation of alignment with respect to the line of sight in the different sources: indeed, correlations between optical interstellar polarization and extinction are seen only in particular clusters or clouds (Hall and Serkowski, 1963) and not amongst stars observed in different directions in the galaxy. In the molecular clouds extinction estimates are made unreliable by the possibility of residual silicate emission and the non-correlation of ice and silicate optical depths (Merrill et al., 1976).

b. The Relationship Between Interstellar and Molecular Cloud Polarization. We pointed out above that the most likely interpretation for the BN polarization data is that light from the source passes through a medium of aligned grains. Dyck and Beichman (1974) and Dennison (1977) have argued that the alignment mechanism is the galactic magnetic field compressed to a strength of several milligauss during the evolution of the Orion Molecular Cloud. Kobayashi et al. (1978) and Dyck and Lonsdale (1979) have pointed out that if one accepts this interpretation as generally valid for molecular cloud sources then one might expect a correlation between the field directions inside the cloud and in the vicinity of the cloud. The best way to look for such a relationship is to compare the position angle of polarization for a particular cloud source with the position angles of visual interstellar polarization delineated by OB stars near the cloud. From a study of 28 sources Dyck and Lonsdale (1979) showed that the infrared position angles for 70% of the sample lay within 30° of the mean interstellar polarization direction in the immediate vicinity of those sources. Since that study three additional sources have been observed (NGC 7538/IRS 4, L 1630 #41 and GL 961) which also have interstellar polari-

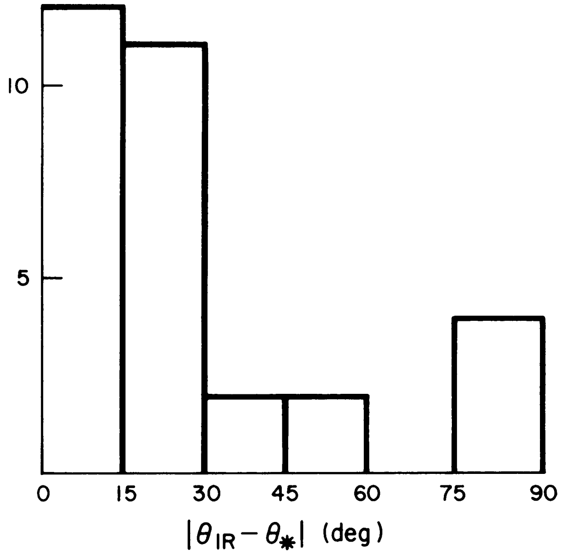

Figure 4 - A plot of the distribution of differences between infrared and interstellar polarization position angles.

zation data available, bringing the total to 31. A plot of the absolute value of the difference between the mean interstellar and the infrared polarization directions is shown in Figure 4. The position angles for the three new sources lie within 30° of the mean interstellar direction bringing the fraction to 75% of the 31 which show close agreement between the two directions. There is a strong correlation between the two sets of position angles, and therefore, justification for seeking a common mechanism for interstellar and molecular cloud polarization. To the extent that one believes that the galactic magnetic field is responsible for aligning grains which produce interstellar polarization then one must believe that it is responsible for grain alignment in molecular clouds. We conclude that this evidence demonstrates that the galactic magnetic field plays an important role in molecular cloud evolution, remaining trapped for a significant fraction of the lifetime of the cloud.

c. The Circular Polarization. Circular polarization has been searched for at 2.2 μm in nine of the molecular cloud sources including BN and GL 2591, and detected in five. It has been interpreted in terms of the aligned grain model (Lonsdale et al., 1980). As noted above, circular polarization has not been considered in the scattering model. In Figure 5 we have plotted all the available circular polarization data against linear polarization for the seven molecular cloud sources, and also for GL 2688, an object known to be a bi-polar nebula. Within

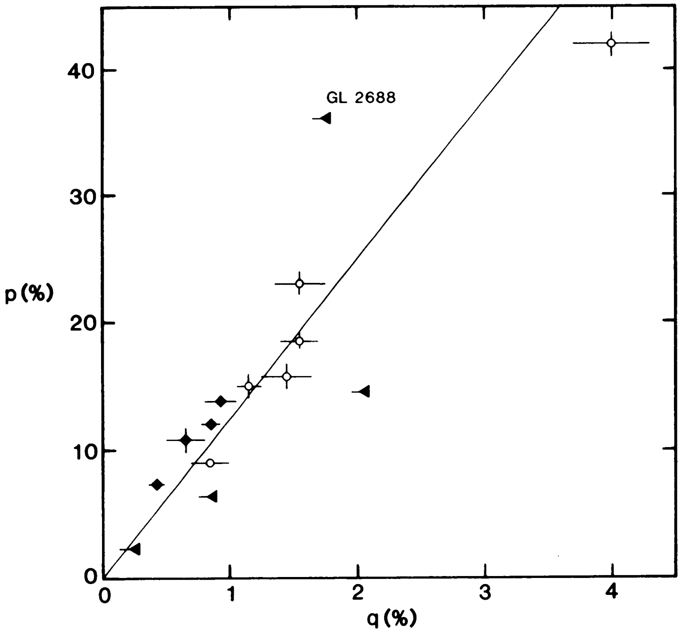

Figure 5 - Infrared circular (q) versus linear (p) polarization for a number of molecular cloud sources and for the bi-polar nebula GL 2688. The open circles are data for BN between 1.6 and 3.5 μm. The data were taken from Serkowski and Rieke (1973), Johnson (1979), Lonsdale et al. (1980), and from unpublished observations of GL 2688 made at Mauna Kea. The solid line, q = 0.08p, is shown for reference only. The triangles are 3σ upper limits to q.

the uncertainties of the measurements, GL 2688 shows a significantly lower ellipticity than the molecular cloud sources.

Aligned grain models which account for the circular polarization predict rotations or twists in the direction of grain alignment along the line-of-sight to the sources of the order of 20-80° (Lonsdale et al., 1980; Martin, 1980, private communication).

4. DISCUSSION

From the foregoing discussion the following conclusions arise:

I. The most plausible explanation for the polarization of BN is that it arises by transfer of radiation through a medium of aligned grains within OMC 1.

II. Since the position angles of polarization of the majority of the remaining sources in the sample correlate with those of the neighboring interstellar polarization, it is likely that the polarization mechanism is the same for these sources as for BN.

If the aligned grain model is adopted as correct, then some interesting consequences result.

a. Martin (1975), Capps (1976), and Capps and Knacke (1976) have inferred that the behavior of the ratio of polarization to optical depth within the 10 μm silicate band indicates that the interstellar silicates have a lower bandstrength than terrestrial crystalline silicates. This may indicate that they are amorphous.

b. The aligned grain models for BN and GL 2591 are crude and non-unique because of observational and computational ambiguities. For Rayleigh particles composed of pure ices and silicates the computed polarization spectra do not match the observations exactly. In order to improve the match the models may require either significantly larger particles (i.e., ones with a significantly larger scattering cross-section) or a change of composition (Dyck and Lonsdale, 1980; Lonsdale et al., 1980).

c. Gull et al. (1980), in their search for far infrared polarization, expected to observe polarization in emission from the grains which polarize by absorption at the shorter wavelengths. Such polarization would have a position angle 90° from that of the absorption polarization. The detection of polarization at 75-115 μm with a position angle similar to that of the shorter wavelength data would indicate that the polarizing region is still optically thick at these wavelengths.

d. The galactic magnetic field must have a strong influence inside the molecular clouds. Also the grain alignment mechanism must operate successfully within the clouds, and rotations or twists may exist in the direction of alignment through the cloud. Such rotations are not inconsistent with the interstellar field-infrared source position angle correlation: models would predict the two to agree within one half of the rotation angle (Martin, 1974), i.e., of order 10-40°, if there are no significant variations in grain composition along the line of sight in the cloud.

These conclusions leave us with several questions to answer. How is grain alignment effected within the dense molecular clouds? How strong do the magnetic fields have to be to produce the necessary alignment? What causes the twists in the grain alignment? To aid in answering these questions, and of independent great interest to theorists, would be the knowledge of where in the cloud does the polarization arise: do the variations in polarization between individual members of a complex arise because the objects are situated at different depths in a fairly uniform region of aligned grains throughout the cloud; or are the polarizing regions associated more closely with individual sources? Careful polarimetric work is required to answer these questions from an observational standpoint.

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DISCUSSION FOLLOWING PAPER DELIVERED BY H. M. DYCK

T. L. WILSON: Do you have any specific mechanism for aligning the grains by which you can make an estimate of the size of the magnetic field?

DYCK: I do not believe that this problem can yet be properly answered; naive calculations using the Davis-Greenstein mechanism give unreasonably large magnetic fields, of order 10^{-3} Gauss for the Orion cloud, which I am reluctant to believe.

T. L. WILSON: In any case, the Davis-Greenstein mechanism could not work in the Orion cloud because observations show that the gas and dust have the same temperature.

ALLAMANDOLA: I spoke with Ted Simon last week at JILA and he has data which show some evidence for a correlation between polarization and strong absorption at 3.1 μm, i.e., the ice band. We believe that the ice band is an indication of the presence of a mantle, although mantles do not have to have a prominent ice band. In our experiments in Leiden we are irradiating these complex molecular mixtures and find that radicals—that is, molecular sub-units which have unpaired electrons—are formed and stored. Having unpaired electrons in grains will alter the magnetic properties significantly increasing the magnetic susceptibility. Alignment via a Davis-Greenstein mechanism should then be possible without requiring unreasonably strong magnetic fields.

OKUDA: As for the linear polarization of the BN object at 3 μm band, Kobayashi has observed a spectral dependence of the polarization and found a small shift in the peak to longer wavelengths compared with the peak of the extinction. The shift can be explained well by theoretical calculation, adopting optical properties of water ice.

ELSASSER: In former publications a relation between the compactness of infrared sources and polarization was found. Is there anything new about this phenomenon which would be an essential hint to the mechanism?

DYCK: I would refer to this effect as a tendency rather than a strong correlation. Sources with a diameter smaller than about 10^{17} cm tend to be highly polarized, but there are notable exceptions such as IRS 1 in Mon R2 which is more than 20% polarized, but which is apparently extended.

T. JONES: Do you attach any significance to the $\lambda^{-2.4}$ power law in the BN source?

DYCK: Simply that the exponent in the power law is different in the BN source and in GL 2591.

BECKLIN: You used the fact that in Orion there is no radial symmetry around BN in the polarization vectors to argue against the reflection nebula hypothesis. However, the Orion cloud contains several sources of luminosity. Could it not be that each of these has an anisotropic dust distribution around it, but that there is some large-scale factor in the region, perhaps angular momentum, which aligns the asymmetries of the different objects?

DYCK: I agree that is possible, but such a mechanism would not lead to the relationship we find between the directions of polarization in infrared sources and in nearby stars. Additionally, we find that in general the direction of infrared polarization does not correlate with Galactic rotation in any easy way.

ELSASSER: The model of Staude and Elsässer was constructed because we believe, together with other authors, that it is difficult to understand the high degree of polarization found in different sources by magnetic alignment of elongated particles (Davis-Greenstein mechanism). Our model offers several tests and the new observations mentioned by Dr. Dyck show that it cannot be applied to the BN source in the way we tried. On the other hand, new results of Schulz and Lenzen of our institute on highly obscured M17 stars with polarization degrees up to nearly 30% pronounce again the difficulties of the Davis-Greenstein mechanism.

HARWIT: We have measured the 100 μm polarization of the Kleinmann-Low Nebula and find it to be $\lesssim 1\%$. This is puzzling. We had hoped to see linear polarization in emission and to find it oriented perpendicular to the direction seen in absorption in the near infrared. It suggests that the interior of the nebula might lack conditions conducive to alignment; perhaps either the alignment directions are jumbled, or there is thermal equilibrium between the gas and dust.

BECKWITH: Have you looked for correlations between overall rotation of the molecular clouds and the direction of the polarization? If, as you have suggested, the magnetic field causes grain alignment, then the correlation between the interstellar visual polarization and the infrared polarization suggests the field energy dominates the internal energy in the cloud, and you can obtain a lower limit on the field energy.

DYCK: In most cases there are not enough radio observations to establish the rotation direction of the molecular clouds associated with these infrared sources. It would be extremely valuable if radioastronomers could provide us with these data.

ZUCKERMAN: Don't hold your breath waiting for radioastronomers to solve that problem.

T. L. WILSON: The rotation of molecular clouds is difficult to measure. In Orion, there are 2 cold clouds ($T_k \simeq 70$ K) near BN/KL. To the measurement accuracy, these clouds are not rotating, and have apparently different shapes. Hence the similarity of the polarization over the Orion Molecular Cloud seems not to be simply connected to angular momentum in the clouds.

KRISCIUNAS: Your histogram of the difference of position angles of polarization of sources versus the general field polarization [Figure 4] implies a variation of grain shapes from source to source. Do you feel the number of sources you observed is large enough to validly conclude this, and, if so, are you trying to model particular grain shapes in these sources?

DYCK: I think that to draw conclusions about differences in grain shape from source to source we need to draw on other kinds of data than those in Figure 4.