The Interpretation of Polarization Position Angle Measurements

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Abstract. I review the use of polarization data in the study of interstellar magnetic fields. On large scales in the interstellar medium, the polarization of background starlight is a good tracer of the projected plane-of-the-sky magnetic field structure in the neutral gas, and the field there appears to have roughly equal contributions from uniform and non-uniform components. In cases where a localized region (e.g. a dense, star-forming cloud) is of interest, polarimetry of background starlight may give a misleading impression of the field structure. In these dense regions, polarized thermal emission may be a more reliable tracer of the magnetic field—assuming the grains are aligned by magnetic fields.

1. Scope

The emphasis of this review is on using polarimetric observations of background starlight and thermal dust emission to understand the structure of the magnetic field in the Milky Way’s interstellar medium [ISM]. Specifically, it focuses on dark cloud complexes and other regions of star-formation.

In order to avoid significant overlap with other reviews in this volume, I do not discuss the structure of magnetic fields in: circumstellar regions (see Bastien); the Galactic Center (see Davidson, Roche); the Milky Way as a whole (see Heiles, Zweibel); very diffuse gas (see Zweibel); the warm ISM (see Heiles); or any extragalactic objects (see Beck, Hough). The discussion of polarized thermal emission from dust in this chapter is limited, and readers are referred to the chapter by Hildebrand for a more extensive review.

2. Historical Perspective and Context

The polarization of background starlight was discovered nearly 50 years ago, but we still do not know exactly how to interpret it. We are relatively certain that aligned, asymmetric dust is responsible for producing polarization of background starlight (as well as thermal emission), but we still are far from sure of the mechanism(s) which align the grains.
2.1. Observational Discoveries

In 1949, Hall and Hiltner independently discovered that the light from the great majority of stars is partially linearly polarized (Hall 1949; Hall and Mikesell 1949; Hiltner 1949b; Hiltner 1949a; Hiltner 1950). They found that: 1) neighboring stars had similar polarization directions, which indicated that the polarization process was not likely to be intrinsic to the stars; and 2) the measured percentage polarization (typically a few percent) appeared to be weakly correlated with color excess (see Figure 1). These two empirical findings led to the conclusion that the same interstellar dust which causes reddening ("color excess") and extinction can also cause polarization. It follows that any "background" starlight polarization observation represents the cumulative effect of all polarizing encounters between star and observer.

Many proposals have been made to explain the polarization of background starlight (Section 2.2), most of which rely on magnetic alignment of elongated grains. When grain alignment is magnetic in origin, maps of the polarization of background starlight give information about the superposition onto the plane of the sky of all magnetic fields along the line of sight to the background star.

In 1970, Mathewson and Ford collected observations of the polarization of background starlight for 1800 stars in the Milky Way (see also Mathewson et al. 1978). The Mathewson and Ford data gave the first view of the magnetic field structure of the Galaxy, showing that locally the field follows the projected outlines of the H I bubbles discovered by Heiles and Habing (1974), and at 2-4 kpc the field direction appears to follow the Galactic spiral arms (see figure and discussion in Whittet 1992).

Upon seeing Mathewson and Ford’s survey, most of the astronomical community believed that polarization of background starlight was caused by magnetically aligned grains, and the quest to understand the mechanism producing the polarization was renewed. An important clue was found when Serkowski, Mathewson, and Ford (1975) empirically quantified what is now known as the "Serkowski Law" for the wavelength dependence of polarization, \( p(\lambda) \). Studies
of the behavior of $p(\lambda)$ can give information about which grains along a line of sight are producing polarization, making it easier (in principle!) to understand where along the line of sight polarization is produced.

In the 1970’s, it was hypothesized that a map of the polarization of background starlight for stars around the periphery of an individual nearby dark cloud would give a map of the plane-of-the-sky magnetic field, $\vec{B}_1$, in that cloud, since virtually all of the dust along the line of sight would be located at the distance of the cloud. In 1976, Vrba, Strom, and Strom published five such “dark cloud” polarization maps (Vrba et al. 1976; hereafter VSS). At about the same time, it was becoming apparent that magnetic fields might play an important role in the star-formation process (Mouschovias 1976a; 1976b). So, when star-formation community wanted to know more about magnetic field structure, it looked to the VSS maps, and to the several other maps of the peripheries of
dense clouds created in the following two decades.\footnote{See Myers & Goodman 1991 for a compilation of background starlight polarimetry data sets.} Figure 2 shows an optical polarization map of the Taurus dark cloud complex.

In efforts to investigate magnetic fields within the “dark” portions of dense interstellar clouds, the background-starlight-polarimetry industry branched out into the near-infrared. The expectation was that near-infrared observations would reveal fields associated with denser gas by looking “through” the visually opaque dark clouds. In actuality, this reasoning may be flawed (see Section 4.2), but several researchers (including the author!) used it over the past two decades to justify mapping the polarization of near-infrared background starlight—which is indeed visible “through” dark clouds—for a variety of extended dense regions (e.g. Wilking et al. 1979; Jones et al. 1984; Hodapp 1987b; Hodapp 1987a; Tamura et al. 1987; Sato et al. 1988; Tamura et al. 1988; Klebe and Jones 1990; Goodman et al. 1992; 1995).

In 1966, Stein argued that if aligned dust produces the polarization of background starlight, then thermal emission from dust should be partially linearly polarized as well (see also Dennison 1977). Polarized thermal emission from dust has now been observed at several wavelengths, ranging from the mid-infrared (e.g. Knacke and Capps 1979) to the millimeter (e.g. Leach et al. 1991), with the bulk of the observations at sub-mm and far-infrared wavelengths, where dust emission is strongest. These observations are discussed in greater detail in Hildebrand’s chapter and in Sections 4.2 and 5 below.

2.2. Theoretical Milestones

The discovery of the polarization of starlight in 1949 immediately prompted active speculation as to its physical origin. By 1951, Davis and Greenstein (Davis and Greenstein 1951; hereafter DG) had proposed a theory which is still accepted as a basic paradigm today. In the DG scenario, the interaction of the external magnetic field with paramagnetic grain material causes grains to “relax” into a lowest-energy state where the external field and the grain paramagnetic moment are aligned. The grains aligned by this process are presumed to be elongated and spinning about their shortest axis, which produces partial linear polarization parallel to the short axis of the grain. The timescale for alignment of a grain’s rotation axis with its short axis is very short (\(\sim 1\) yr; see chapters by Lazarian, Jones, and Roberge); but the timescale for the DG relaxation process is very long (\(\sim 10^6\) yr). In fact, over the past forty-five years, several authors have pointed out that the DG relaxation timescale for “typical” interstellar conditions is likely to be much longer than the time between disorienting grain collisions (\(\sim 10^4\) yr; e.g. Spitzer and McGlynn 1979), so that DG relaxation is far too inefficient to explain the observed levels of polarization on its own. It is important to realize, however, that the short axis of even an imperfectly aligned grain will still precess about the magnetic field direction (Purcell 1979), and produce polarization in the same direction (along \(\vec{B}_\perp\)) as an “aligned” grain, but with much lower efficiency.

In 1967, Jones and Spitzer proposed a modification of the DG mechanism in which grains contained “superparamagnetic inclusions” (i.e. Fe-containing...
particles). The inclusions would enhance the imaginary part of the magnetic susceptibility of the grain material by a factor of \( \sim 10^6 \), which would in turn produce enough grain alignment to explain observations. This “SPM” hypothesis has since been offered some additional support. In 1986, Mathis showed that it offers a natural explanation for the observed \( p(\lambda) \) relationship, and recently Goodman and Whittet (1995) showed that the particles found embedded in interplanetary dust particles which are alleged to be interstellar grains (see Bradley 1994; Martin 1995) contain SPM inclusions with the right spatial frequency to support Mathis’ conclusions.

Another enhancement to the DG mechanism was proposed by Purcell in 1979. In the original DG scenario, the spin of the grains was caused purely by thermal interactions, and it was quite slow (\( \sim 10^5 \) rad s\(^{-1}\)), allowing the grains to become easily disoriented. Purcell proposed a variety of mechanisms which could substantially enhance the grain’s rotation rate, and hence its stability against disorienting collisions. The most popular “suprathermal rotation” mechanism proposed by Purcell envisions the “active sites” on grain surfaces, where atomic H combines to form H\(_2\) (Hollenbach and Salpeter 1971), as rockets which spin up the grain (to angular speeds \( \sim 10^9 \) rad s\(^{-1}\)) each time a newly formed H\(_2\) molecule is ejected from the surface. If this particular process is key to producing substantial polarization of background starlight, then polarization efficiency\(^2\) would potentially be very low in dense clouds, where most of the hydrogen is already molecular (Johnson 1982).

Many alternative grain alignment mechanisms have been proposed since 1951 (see chapters by Lazarian and Roberge), but the modern version of the DG scenario (including superparamagnetic and/or suprathermal grains) is thought to cause most of the grain alignment in the ISM. The possibility that variations in the efficiency of this mechanism may play a key role in the interpretation of polarization maps is discussed in Sections 3.2 and 4.

Theorizing on the distribution of polarization vectors in polarization maps began almost immediately after the discovery of the polarization of background starlight. Chandrasekhar and Fermi (1953; hereafter CF) devised the first systematic method for analyzing the dispersion in polarization position angle (see Section 4.1 and chapters by Heiles and Zweibel). Jokipii and collaborators extended the CF analysis during the 1960’s and 70’s (Jokipii et al. 1969; Jokipii and Parker 1969a; Jokipii and Parker 1969b; Jokipii and Parker 1969c; Nee and Jokipii 1979). Several recent extensions and applications of the CF technique are discussed in Section 4.1.

2.3. Polarimetry in Context

It is best to analyze polarimetric measurements in concert with other sources of information about magnetic field structure. For the most part, such comparisons are only possible on very large scales, utilizing measurements of the field in

\(^2\)I use “polarization efficiency” to refer to the amount of polarization, per unit extinction, produced by a grain. Jones’ calls this “polarizing power” in his chapter.
the warm ionized ISM.\textsuperscript{3} Heiles’ chapter describes how observations of rotation measure and dispersion measure along lines of sight to pulsars at “known” distances are used to probe the field in the Galaxy. Observations of polarized radio (synchrotron) emission from the ionized ISM of other galaxies are discussed in the chapter by Beck. The results discussed by both Beck and Heiles give the impression that the large-scale magnetic field in spiral galaxies exhibits a spiral pattern with a “uniform” component of the field following spiral arms. That picture is consistent with the Mathewson and Ford (1970) background starlight polarimetry observations of the Galaxy.

3. Understanding the Polarizing Process(es)

The interpretation of polarization position angle maps depends critically on modeling exactly how and where along a line of sight polarization is produced. While it is often possible to infer the line-of-sight density distribution of dust, not all dust is equally efficient at polarizing radiation. The uncertainty in the line-of-sight dependence of polarization efficiency makes it very difficult to uniquely interpret polarization maps. Suffice it to say that the better the model for the production of polarization along the line of sight, the better the interpretation of a polarization map.

3.1. Non-magnetic polarizing processes: Scattering

Before interpreting any polarization, it is necessary to establish whether the polarization observed is caused by grain alignment or some other process. At optical and near-infrared wavelengths, light scattered off of interstellar (or circumstellar) dust is strongly polarized. When a star is surrounded by a large amount of circumstellar material, often the only optical or near-infrared radiation observed “from” the star is scattered light.\textsuperscript{4} Fortunately, in analyzing polarization maps of background starlight, it is usually easy to exclude so-called “intrinsically polarized” stars, based on gross disagreement of $p(\lambda)$ measurements with the Serkowski Law, and on their high percentage (\textasciitilde tens of percent) polarization.

3.2. Grain Properties and Grain Alignment as Functions of Physical Conditions

In an ideal (but boring) universe, dust grains would all be identical and perfectly aligned, and the task of interpreting polarization maps would be easy. In our Universe, however, there are significant variations in grain properties (see chapters by Draine, Mathis, and Sandford), and in grain alignment (see chapters by Jones, Roberge, Whittet, and Lazarian), which can cause significant variations in polarization efficiency along the line of sight. To interpret a polarization map,

\textsuperscript{3}In cases where Zeeman “maps” of the line-of-sight field strength are available, comparisons can be made between plane-of-the sky and line-of-sight field structure in the cold neutral ISM (see Section 4.1).

\textsuperscript{4}Young, heavily embedded stars are seen primarily in highly polarized scattered light; see chapter by Bastien and references therein.
we need to know how much dust of a particular polarizing efficiency is located at each position along a line of sight. Despite careful studies of so-called “environmental” variations in polarization efficiency (e.g. Gerakines et al. 1995), it is not yet possible to reliably model individual lines of sight. And, let me not forget to mention that although most alignment schemes are magnetic in origin, and predict that a grain’s short axis will align with the magnetic field, not all of them do (see chapters by Jones, Lazarian and Roberge).

In special cases, it is possible to either circumvent or understand the problem of line-of-sight variations in polarization efficiency. For example, if one observes polarization produced along very long lines of sight where environmental conditions “average out,” one can assume a constant (although perhaps unknown) polarization efficiency in order to model magnetic field structure. This technique has been successfully applied by Jones and his collaborators (Jones 1989; Jones et al. 1992; JKD; see Section 4.1), who assume “perfect” grain alignment in modeling the field, which is equivalent to assuming constant alignment efficiency. Efficiency variations can be assumed to average out for lines of sight to very distant stars seen through the low-density galactic ISM, and probably for polarimetry of external galaxies.

Along lines of sight where almost all of the polarization is produced in a localized region, efficiency variation difficulties can also be minimized. One might reasonably expect (Section 2.1) polarimetry of background starlight passing through nearby dark clouds to be an example of this “localized” case (Vrba et al. 1976), but recent results have shown this expectation to be overly optimistic (Section 4.2). In far-infrared and sub-mm emission polarization maps, when virtually all of the emission is known to come from a particular region along the line of sight, it may be easier to understand polarization efficiency variations (see Section 5 and Hildebrand’s chapter).

Observations of the polarization of spectral features can also help in sorting out which grains along a line of sight are responsible for polarization (e.g. polarized ice features must arise in cold regions; see chapters by Sommerville and Aitken). By combining the spectropolarimetric results of Aitken et al. (1985; 1988) with far-infrared and background starlight observations, Hildebrand and Dragovan (1995) have placed some important new constraints on the average properties of polarizing grains, but more work is needed before we can associate grains with particular polarizing properties with particular environmental conditions.

3.3. Polarization as a Function of Extinction

Analyses of polarization as a function of extinction give quantitative information on polarization efficiency. In the simplest case, where every grain extinguishing light also polarizes it, and the magnetic field is uniform, polarization and extinction should be tightly correlated. However, from even the earliest observations, it was obvious that polarization, $p$, and extinction, $A_V$, are not generally well-correlated (despite Hall’s caption for Figure 1a!).

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5The term “polarization as a function of extinction” has traditionally applied to background starlight observations, but easily translates to “polarization as a function of optical depth” for thermal emission polarization observations (see chapter by Hildebrand).
Since the magnitude of $p$ depends on the orientation of the magnetic field, $\vec{B}$, but $A_V$ does not, the $p$ vs. $A_V$ relation for any region which contains variations in the orientation of $\vec{B}$ will not be a perfect straight line. Instead, at any value of $A_V$, any value of $p$—up to the limit given by perfect alignment and a purely plane-of-the-sky field—can be observed. (Even for perfect alignment, if $\vec{B}$ is exactly along the line of sight, no polarization will be observed, regardless of $A_V$.) Careful inspection of Figure 1a easily reveals this behavior.\(^6\) Changes in the orientation of $\vec{B}$ are usually sorted into two categories. The first category deals with the so-called “mean” or “uniform” field, and the second deals with the “fluctuating” or “non-uniform” field. Polarization efficiency depends on both changes in the inclination of the uniform field with respect to the line of sight and the amount of “non-uniformity” or tangling in the field (see Jones’ chapter and Section 4.1).

While geometry can go far toward explaining the wedge-shaped appearance of Figure 1a, it cannot explain the polarization-extinction relations seen in some background polarimetric data sets which sample specific objects, such as cold dark clouds. In those regions (Section 4.2), there are apparently, real (i.e. non-geometric) variations in polarization efficiency along the line of sight. It is not yet clear whether the variations are due to changes in grain alignment, or grain properties, or both (see Goodman et al. 1995; hereafter GJLM).

In general, an interpretation of a polarization map cannot be considered complete without at least a hypothesis about polarization efficiency variations along the line of sight. Polarization-extinction relations, often along with $p(\lambda)$ measurements, provide some of the most useful data on which to base hypotheses about these variations.

4. Interpretation of Polarization Position Angle Maps

Analysis of polarization maps\(^7\) typically takes one of two forms. The first can be called “global analysis” and treats the data set without regard to the details of the spatial variations in polarization percentage and polarization position angle. The second method deals specifically with the spatial variations in polarization, and can be called “structural analysis.”

4.1. Global Analysis

Figure 3 shows a position angle histogram for the Taurus polarization map in Figure 2. The mean of the distribution ($48^\circ \pm 1^\circ$) gives the position angle of the “mean” or “uniform” field for the Taurus dark cloud complex. The $1\sigma$ dispersion in the distribution, $s(= 0.43 \pm 0.01 \text{ rad})$, gives information about the non-uniform field. In 1953, Chandrasekhar and Fermi wrote down the first

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\(^6\)Empirically, the upper limit to the $p$ vs. $A_V$ relation is $p_V [\%] = 9E(B-V)[\text{mag}] = 3A_V [\text{mag}]$ (Whittet 1992).

\(^7\)I define a “polarization map” as a set of polarization measurements taken in a particular region of the sky for the purpose of studying that region. For example, the Mathewson and Ford (1970) data set is a polarization map of the Milky Way, and Figure 2 is a polarization map of Taurus.
Figure 3. *Polarization Position Angle Distribution for the Taurus Dark Cloud Complex* Histogram shows observed number distribution of position angle for the data set pictured in Figure 2. Solid and dotted lines show fits used to determine the width of the distribution (MG).

Myers and Goodman (1991; hereafter MG) have analyzed polarization position angle distributions for more than a dozen regions with a technique similar to the CF method. In the MG formalism, for a single-peaked distribution like the one in Figure 3, and three-dimensional fluctuations in the field,

\[ s = \frac{\sigma_B}{N^{1/2} B_{ox}}, \]  

where \( \sigma_B \) is the 1σ dispersion in a gaussian-random non-uniform field, \( B_{ox} \) is the strength of the plane-of-the-sky component of the uniform field, and \( N \) is the number of correlation lengths of the field along the line of sight. \( N \) is usually estimated by assuming that the number of correlation lengths along the line of sight is similar to that in the plane of the sky, so that \( N \sim 3 \) for the Taurus map (Figures 2 and 3). For Taurus, \( s = 0.43 \) radians, which implies that the ratio \( \frac{\sigma_B}{B_{ox}} \approx 1 \), for \( N = 3 \). MG estimate that the ratio of non-uniform to uniform field *energy* is typically of order unity for large dark cloud complexes, and somewhat larger for dense gas with embedded clusters.

Both the CF and the MG methods can be used to combine polarimetric observations with other observations to estimate field strength. In the CF picture, the additional observations are of gas velocity dispersion and density, and \( s \) is essentially used to estimate the amplitude of wavelike fluctuations which give rise to the observed velocity dispersion (see Zweibel’s chapter). In the MG
method, a distribution of line-of-sight field strength, \( B_0 \), derived from Zeeman measurements is used to find the magnitude of the mean line-of-sight field and the magnitude of the non-uniform field. The Zeeman information is then combined with the polarimetric value for \( s \), yielding an estimate of the three-dimensional mean field, \( \vec{B} \).

Jones (1989) and JKD have modeled position angle distributions and the polarization-extinction relation by breaking down the field into “uniform” and “non-uniform” components, and using optical depth steps (instead of physical length) as the natural correlation length for the uniform field. The number of optical depth steps traversed by a photon along its path from background star to observer is equivalent to MG’s “\( N \),” and both models find that large data sets which do not include any “special” regions (e.g. embedded clusters) are best-fit with a ratio of non-uniform to uniform field of order unity. The Jones/JKD model predicts that the dispersion in polarization position angle, \( s \), should decrease as column density increases, as long as the ratio of non-uniform to uniform field remains fixed. (Note that increasing column density in the Jones/JKD model is equivalent to increasing \( N \) in equation 1). This prediction is verified when lines of sight where polarization efficiency “averages out” are considered, but is notably violated when considering cold dark cloud position angle distributions. The Jones/JKD prediction for polarization as a function of optical depth (i.e. \( p \) vs. \( A_V \)) is also borne out for “average” lines of sight, but violated for cold dark clouds (see Figure 5). These agreements and disagreements of model and data are discussed further in Jones’ chapter and in Section 4.2.

4.2. Structural Analysis

Large Scale Optical and Near-Infrared Polarization Maps

As discussed above, subtle differences in the polarizing properties of grains tend to average out over large distances or large data sets. As a result, polarization maps of large regions (i.e. the Galaxy, external galaxies, whole dark cloud complexes) are likely to be simple projections of the magnetic fields along the line of sight onto the plane of the sky. The gross geometric features of these maps provide extremely useful insights into large-scale field structures. For example, both the Mathewson and Ford (1970) data set and polarimetry of external galaxies indicate that field lines roughly follow spiral arms in spiral galaxies. The large wave-like structure evident in the Taurus polarization map in Figure 2 is likely to be physically meaningful on scales commensurate with its apparent wavelength (\( \sim 10 \) pc).

The “rub” comes when we try to interpret structural relations on scales where there are large variations in polarization efficiency, or in the number of grains associated with a particular position angle of the field. For example, one would not want to use the polarization map of Taurus in Figure 2 to compare the orientation of a 1000-A.U.-long jet from a young star with the “local” magnetic field direction, for at least two reasons. First, small-scale inhomogeneity in the field is easily washed out in maps of the polarization of background starlight—it may only show up as an increase in the dispersion of polarization position angle. Second, near-infrared polarimetric results like the ones discussed below

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8See Heiles and Zweibel’s chapters for comparisons of these polarimetric field uniformity estimates with estimates based on pulsar data.
Figure 4. Top: Optical polarization map of the B216-217 Dark Cloud, from Heyer et al. (1987b). Middle: Infrared polarization map of the B216-217 Dark Cloud from Goodman et al. (1992); two unpolarized stars are shown as asterisks, whose size is proportional to the limit on $p_K$. Bottom: Superposition of optical and infrared polarimetry based on the data shown in the two panels above. Note that the infrared data have been darkened in the bottom panel, and unpolarized sources are not shown. The length of the vectors is proportional to $p_K$ for the infrared data, and $p_V$ for the optical data, with the scale as indicated, in all panels.
A V [mag]  

Range for Filaments

L1688 (Wilking et al. 1979)
H C12 (Tamura et al. 1987)
NGC 1333 (Tamura et al. 1988)

A V [%]

H216-217 (Goodman et al. 1992)
L1755 (Goodman et al. 1995)

k T [%]

L1755 (Goodman et al. 1995)

B216-217 (Goodman et al. 1992)
Figure 5. Observed relationships between polarization and extinction in dark clouds. Upper panel: Data for filamentary dark clouds. Lower panel: Data dark clouds which are close to round, in projection, and produce higher extinction than typical filamentary clouds. Both panels show effective K-band polarization on the y-axis. Dashed lines in each panel show error-weighted least-squares linear fits to the data points. Solid lines show the predictions of the JKD model, assuming equal non-uniform and uniform magnetic field energy.

Indicate that gross variations in polarization efficiency may render small, cold, dense regions virtually invisible in background starlight polarization maps. So, in general, it is not prudent to extrapolate field structure from large scales to small.

Does Background Starlight Polarimetry Probe Dense Regions? GJLM have recently published a detailed discussion of the inability of background starlight polarimetry to reveal magnetic field structure in cold dark clouds. Below, I will use B216-217 as a case study of a dark cloud, since it is part of the Taurus dark cloud complex already considered in some detail above (see Figures 2 and 3). GJLM present data for the dark cloud L1755, which is part of the Ophiuchus complex.

There are three observational facts which lead to the conclusion that cold dark clouds are inefficient polarizers of background starlight. Fact 1 (Figure 4): Near-infrared observations of the most highly extinguished regions of cold dark clouds ($A_V \approx 10$ mag) show a pattern of polarization vectors identical to what one would simply extrapolate from optical observations made around the periphery of the clouds ($A_V \approx 1$ mag). Fact 2 (see Figure 2 of Goodman et al.
Figure 6. Changes in the efficiency of polarization associated with dark clouds. Top panel shows a hypothetical distribution of extinction for a line of sight through a dark cloud. Middle panels show particle density and polarizing efficiency, as functions of distance from the observer, assuming the extinction distribution in the top panel. The drop in polarizing efficiency associated with the dark cloud produces a polarization-extinction relation similar to that sketched in the bottom panel. The “?” illustrates that we do not know the exact shape of this relation, and that we expect it to vary from region-to-region. (GJLM)

1992): The mean and dispersion in the position angle distribution for optical and near-infrared data sets are identical—even though the near-infrared lines of sight look “through” the dark cloud and the optical observations only trace the periphery of the cloud. These first two facts together imply that either: a) the tremendous density enhancement represented by the dark cloud is having no effect on the magnetic field there; b) field dispersion increases in the dark cloud in exactly the right way so as to mask changes in the field (see equation 1); or c) near-infrared polarimetry is not sensitive to the field inside the dark cloud. But (Fact 3 (Figure 5)) the fact that polarization does not rise with extinction inside cold dark clouds is only consistent with choice “c” above (i.e. dark clouds are invisible from the standpoint of background starlight polarimetry).

Any contribution of the grains inside the cloud to the polarization would cause $p$ to rise with $A_V$, even if the field were very tangled. Even a completely
non-uniform field will cause $p$ to rise with $A_V$, in the same way that a random-walker perpetually gets farther from the origin. The solid line in Figure 5 shows the prediction of the JKD model for the case of equal non-uniform and uniform field strength, and clearly does not fit the dark cloud data.

In warmer, rounder, dense regions, polarization efficiency is also reduced (Wilking et al. 1979; Tamura et al. 1987), but perhaps not by as much as in the colder dense gas found in elongated dark clouds. In the bottom panel of Figure 5, one can see that the data for the warmer dense regions (L1688, H Cl 2, and NGC 1333) does show a small rise in $p$ with $A_V$, but that the absolute values of $p$ all fall far short of the JKD prediction. Notice, however, that if only the boxed region labeled “range for filaments” in Figure 5 is considered, then not much of a rise of $p$ with $A_V$ is apparent, even for the warmer sources. This result suggests that new, premeditated, investigations of polarization efficiency as a function of physical conditions are needed.

Several researchers have noted that polarization efficiency appears to be low in dense regions (e.g. Vrba et al. 1976; Wilking et al. 1979; Tamura et al. 1987; GJLM; Gerakines et al. 1995), and the challenge at the current time is to figure out what causes changes in efficiency, how large the changes are, and under what conditions they occur. It is clear that of all the grains in the ISM, only some are any “good” at polarizing light, in comparison with their ability to extinguish it (see Kim and Martin 1994; 1995). In the terminology of Terry Jones, the grains inside cold dark clouds are overwhelmingly “bad” in that they only extinguish light and do not polarize it. Meanwhile, the ambient ISM presumably contains a constant and large fraction of so-called “good” grains (see Jones’ Figures 2 and 4 in this volume and Figure 10 of GJLM). A grain may be “bad” because it is too round, too small, too large, made of the wrong substance and/or poorly aligned. What is needed now is a quantitative understanding of the curves shown in Figure 6, which schematically depicts the large drop in polarization efficiency associated with cold dark clouds.

**Small-Scale Maps: Sites of Star Formation and Outflows** Since stars form inside dense clouds, the “dark cloud problem” discussed above makes it extremely difficult (if not impossible) to use background starlight polarimetry to study the magnetic field on a scale relevant to formation of individual stars or small groups of stars (i.e. sub-parsec scales in dense gas). Before this problem was evident, however, several researchers did use background starlight polarimetry to study the relationship between magnetic fields and outflows from young stars found in dark clouds cores (e.g. Hodapp 1984; Strom et al. 1986; Vrba et al. 1986; Heyer et al. 1987a; Wootten and Loren 1987; Vrba et al. 1988; Reipurth 1989; Hodapp 1990; Mundt et al. 1990; Mundy et al. 1990; Tamura and Sato 1990; Tamura et al. 1990; Morgan et al. 1991). The conclusions about alignment or misalignment of field direction with other physically relevant directions (e.g. outflow axis) drawn in those studies may not stand the test of time.

5. **Thermal Dust Emission**

I must not leave the reader with the impression that I believe we will never know the magnetic field structure in dense star-forming gas. We may never know it
from background starlight polarimetry (which can only probe visual extinctions up to several tens of magnitudes anyway), but we have a good chance of mapping the field by observing the polarization of thermal emission from dust.

In the case of background starlight polarization, only elongated grains within a particular size range will contribute polarization. Grains much larger or much smaller than the wavelength of background starlight being observed will have virtually no effect. As a result, grains in all regimes of the ISM (hot, cold, dense, tenuous, etc.) can contribute to the polarization of background starlight, as long as they are the right size. In the case of emission polarimetry, the critical discriminator is temperature. Blackbody physics clearly implies that a given quantity of warm dust emits more photons at any wavelength than the same amount of cold dust, as long as grain shape, size, and composition remain unchanged. However, if a line of sight is completely dominated by dust at a particular temperature, the emission and polarization observed will be dominated by dust at that temperature. This is the premise behind mapping the polarization of far-infrared emission from dense gas. The idea is that the dust in dense gas may be colder than that in the low-density ISM, but is so much more abundant, that polarimetry will reveal the field in almost exclusively dense gas.

Of course, polarimetry of thermal emission has its difficulties as well. For example, if a dense cloud has a warm envelope, its emission at far-infrared wavelengths might well be dominated by radiation from the envelope. In such a case, one might be able to observe at a longer wavelength (e.g. sub-mm and/or mm) where the contribution from a greater mass of cold dust would outweigh a smaller mass of warm dust.

Most of the emission polarimetry carried out to date has been done with STOKES and its predecessors on the KAO (see Hildebrand’s chapter and references therein), and by a variety of researchers using ground-based mm and sub-mm single-dish telescopes (e.g. Flett and Murray 1991; Leach et al. 1991; Greaves et al. 1994; Minchin and Murray 1994; Greaves et al. 1995a; Greaves et al. 1995b; Holland et al. 1995; Minchin et al. 1995).

In one region, M17, it is possible to directly compare background starlight polarimetry with far-infrared emission polarimetry in detail (see Figure 4 of Goodman 1995). The far-infrared polarimetry (Dotson 1995) shows a smooth field structure, with some features which seem to correspond to the density structure of the star-forming clouds in M17 (see Figure 7 of Hildebrand’s chapter). The background starlight polarimetry (Schulz et al. 1981; Goodman et al. 1996) on the other hand, shows a jumbled pattern which does not resemble the pattern of emission polarization vectors. The detection of strongly polarized emission in M17 implies that there are aligned grains there, and the near-infrared data do show a small rise in polarization with extinction. However, the background starlight polarimetry is clearly not dominated by the grains producing the far-infrared polarization. The background starlight polarization is giving information on fields along the long (2.2 kpc) line of sight to M17, and the far-infrared emission polarimetry is apparently doing a better job singling out the M17 molecular cloud. Thus, the contribution of grains “in” M17 to the polarization of background starlight is small enough so as to make a background starlight polarimetry map a very unreliable indicator of the magnetic field geometry “in” M17.
In the future, new airborne and satellite single-dish observations will allow measurement of the polarization of thermal emission in regions currently below the (rather high) detection threshold. Specifically, the descendant of the KAO/STOKES system to be used on SOFIA and perhaps the ISOCAM and ISOPHOT instruments on the ISO satellite (to be launched in 1995) should allow far-infrared observations of much colder regions than have previously been observed. If the thermal emission from cold dark clouds like L1755 and B216-217 is found to be significantly polarized, this will mean that there are aligned grains in these cold regions, and that their diminished polarization efficiency in transmission must be due to a cause other than lack of alignment (e.g. big grains, or round grains). The SCUBA detector array at the JCMT, and others like it, are close to being able to detect sub-mm polarization with large numbers simultaneous pixels, and these instruments should be able to reveal field structures within very dense star-forming regions, on scales $\sim 10''$.

At higher resolution, the new and expanded mm and sub-mm telescope arrays (e.g. OVRO, BIMA, SMA) have the capability to reveal magnetic field structure at scales truly relevant to the formation of individual stars. Akeson, Carlstrom, and Phillips (1995) have just recently succeeded in polarization of mm-wave dust emission from NGC 1333.

6. Conclusions

When I consider that any polarization observation represents the line of sight integral of a convolution of grain absorbtivity (or emissivity), grain shape, grain population, grain alignment, and magnetic field structure—I am amazed that we can make any sense out of polarization maps. But, we can.

Background starlight polarimetry has shown that: 1) the field in our own Galaxy and other spirals lies roughly along the spiral arms; 2) the field in nearby dark cloud complexes (i.e. Taurus) appears to undulate on length scales similar to the spatial frequency of dark clouds ($\sim 10$ pc); and 3) the ratio of non-uniform to uniform field in much of the ISM appears to be about unity.

We have recently learned that background starlight polarimetry cannot be considered a reliable tracer of the field in cold dense gas, and that it may be less-than-completely reliable in observations of warm dense gas as well.

Very recent observations of the polarization of thermal emission from dust, which are thought to sample only dense gas, show smooth and perhaps understandable field structures in dense star-forming regions. Furthermore, the field structure implied by emission polarimetry often disagrees (as might well be expected) with the field implied by background starlight polarimetry in regions where both have been measured.

At present, emission polarimetry seems to hold the most promise for studying the field in dense regions. Polarization of background starlight is no doubt still useful for studies of large-scale fields and of the properties of interstellar dust. No doubt, though, we may well be writing another review in ten or twenty years which outlines all of the pitfalls and limitations of the thermal emission polarimetry observations which once seemed so promising...
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