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GRAIN ALIGNMENT IN THE TAURUS DARK CLOUD

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ABSTRACT

Variations in the polarization efficiency (p/A) of interstellar grains as a function of environment place vital constraints on models for the mechanism of alignment. In this Letter, polarimetric observations of background field stars are used to investigate alignment in the Taurus Dark Cloud for extinctions in the magnitude range $0 < A_K < 2.5$ ($0 < A_V < 25$). Results show a strong systematic trend in polarization efficiency with extinction, well represented by a power law $p/A \propto A^{-0.56}$. A number of possible interpretations of this result are discussed. Assuming magnetic alignment of the grains, the observed trend may be influenced by such factors as small-scale magnetic field structure, variation of magnetic field strength and coupling of gas and dust temperatures as functions of density, and systematic changes in the efficiency of suprathermal spin as a function of grain surface properties and H/H_2 fraction within the dark cloud.

Subject headings: dust, extinction — ISM: individual (Taurus Dark Cloud) — ISM: magnetic fields — polarization

1. INTRODUCTION

The light from stars obscured by interstellar dust is almost always partially plane-polarized at visible wavelengths, a phenomenon attributed to extinction by aspherical dust grains that are aligned to some degree by the interstellar magnetic field. Alignment is believed to result from an interaction between the rotational dynamics of the grains and the ambient magnetic field, as originally proposed by Davis & Greenstein (1951, hereafter DG). Paramagnetic relaxation results in the grains' tending to become oriented with their angular momenta parallel (and hence their long axes perpendicular) to the magnetic field lines. Although this mechanism is qualitatively highly successful (Mathis 1986), a detailed, quantitative theory of magnetic alignment that is consistent with all existing observational constraints is yet to be formulated. The efficiency of alignment depends on both the properties of the dust grains themselves and on the environment in which they exist. Polarization studies, in conjunction with measurements of other physical and chemical characteristics of dense clouds, may thus be used as observational tools for constraining the alignment mechanism.

The observed degree of linear polarization (p) correlates positively with the degree of extinction (A) due to dust in the line of sight, but with scatter much greater than can be accounted for by observational errors alone. The polarization efficiency of the interstellar medium (ISM), represented by the ratio p/A at some wavelength, is highly nonuniform but subject to an upper limit (e.g., $p_{max}/A_V < 3.0\%$ mag^{-1}; Serkowski, Mathewson, & Ford 1975), representing optimum efficiency. Scatter in p/A below this optimum value might arise because of a number of factors. In a uniform medium with a uniform magnetic field, p/A varies systematically with the angle between the line of sight and the field direction and is greatest when this angle is 90°. A reduction in net polarization arises if the magnetic field is inhomogeneous, as a result of structure within an individual cloud or the presence of two or more clouds with different average field orientations along the line of sight. Of greater interest are variations in p/A induced by changes in the efficiency of alignment as a function of physical conditions. In this Letter, we attempt to isolate the effect of physical environment on polarization efficiency with the aim of enhancing our understanding of the alignment mechanism.

The effects of viewing geometry and depolarization may be minimized by appropriate choice of sample. Our approach is to select data for stars obscured by an individual cloud that displays a relatively uniform macroscopic magnetic field structure. The Taurus Dark Cloud appears to be an excellent candidate. As it is relatively nearby (~140 pc) and ~20° from the Galactic plane, extinction in this area of sky arises almost entirely within the cloud itself (Elias 1978; Straižys & Meištas 1980; Kenyon, Dobrzycka, & Hartmann 1994). The position angle of polarization is generally independent of wavelength (Whittet et al. 1992), consistent with a general absence of discrete cloud components with different wavelength dependencies of polarization. The distribution of polarization vectors in the plane of the sky is fairly uniform over the entire cloud (Moneti et al. 1984; Tamura et al. 1987; Myers & Goodman 1991; Goodman et al. 1992). Although small-scale regions of magnetic complexity associated with individual condensations undoubtedly occur, the macroscopic field (as sampled by field stars) appears to be generally lacking in major inhomogeneities, which suggests that the degree of grain alignment may be the primary factor that determines p/A.

A further advantage of this choice is the fact that the physical and chemical properties of the Taurus Dark Cloud are reasonably well constrained. Zeeman observations indicate magnetic field strengths of a few milligauss (Crutcher et al. 1993). The cloud possesses filamentary structure (see, e.g., Cernicharo, Bacheller, & Duvert 1985), with small, dense cores observed in line emission of gas-phase molecules such as NH_3 and CS (see, e.g., Myers & Benson 1983; Zhou et al. 1989). The cores have typical masses of a few $M_\odot$, gas temperatures of ~10 K, and densities of ~10^4 cm^{-3} (see, e.g., Wilson & Minn 1977) and are active sites of star formation (see, e.g., Lada, Strom, & Myers 1993). Dust grains in the

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TABLE 1

Catalog of Spectral Types, Extinction, and Polarization Data for Selected Stars

Star ID	Spectral Type[a]	A_K (mag)	p_K (%)	σ_{p_K} (%)	p_K/A_K (% mag^{-1})	References
Elias 3	K2 III	0.97	0.65	0.02	0.67	1, 2
Elias 15	M2 III	1.85	2.1	0.4	1.14	1, 3
Elias 16	K1 III	2.72	2.6	0.5	0.96	1, 3
Elias 19	M4 III	0.17	1.20	0.03	7.06	1, 4
Elias 29	G9 III	0.39	0.94	0.09	2.41	1, 4
Elias 30	K0 III	0.46	1.14	0.04	2.48	1, 2
HD 28225	A3 III	0.12	0.34	0.02	2.83	2, 5, 6
HD 28975	A4 III	0.18	0.82	0.11	4.56	4, 7, 8
HD 29333	A2 V	0.20	1.03	0.07	5.15	4, 9, 10
HD 29647	B6–7 IV	0.37	0.64	0.05	1.73	4, 7, 11, 12
HD 29835	K2 III	0.11	0.80	0.06	7.27	4, 6, 10
HD 30168	B8 V	0.14	0.59	0.06	4.21	4, 6, 8
HD 30675	B3 V	0.16	0.64	0.10	4.00	4, 8, 10
HDE 279652	A2 V	0.10	0.20[b]	0.01	2.00	4, 13
HDE 279658	B7 V	0.20	0.38[b]	0.01	1.90	4, 13
HDE 283367	B9 V	0.21	0.36	0.04	1.71	2, 7, 10
HDE 283637	A0 V	0.23	0.54[b]	0.01	2.35	4, 7, 10
HDE 283642	A3 V	0.24[c]	0.42	0.03	1.75	2, 6
HDE 283701	B8 III	0.27	0.73	0.07	2.70	4, 10
HDE 283725	F5 III	0.15	1.12	0.08	7.47	4, 8, 10
HDE 283757	A5 V	0.19[c]	0.67	0.09	3.53	2, 6
HDE 283800	B5 V	0.17	0.69[b]	0.02	4.06	4, 6
HDE 283809	B3 V	0.58	1.48	0.10	2.55	4, 14
HDE 283812	A1 V	0.20	1.11	0.06	5.55	4, 6, 8, 11, 12
HDE 283815	A5 V	0.19[c]	0.57	0.04	3.00	2, 6
HDE 283879	F5 V	0.21[c]	0.86	0.05	4.10	2, 15
R.A. $4^h19^m19^s.7$	···	0.38	0.76	0.07	2.00	16
R.A. 4 19 43.6	···	0.95	1.39	0.09	1.46	16
R.A. 4 20 03.6	···	0.09	0.38	0.06	4.22	16
R.A. 4 20 14.0	···	0.95	0.91	0.13	0.96	16
R.A. 4 20 41.6	···	1.07	0.87	0.12	0.81	16
R.A. 4 20 46.0	···	0.84	0.80	0.16	0.95	16
R.A. 4 20 47.6	···	0.26	0.51	0.06	1.96	16
R.A. 4 20 52.4	···	0.55	0.98	0.12	1.78	16
R.A. 4 20 55.3	···	0.09	0.41	0.05	4.56	16
R.A. 4 21 27.8	···	0.14	1.29	0.09	9.21	16
R.A. 4 21 29.3	···	0.14	0.65	0.08	4.64	16
R.A. 4 22 11.6	···	0.55	1.01	0.20	1.84	16
R.A. 4 22 34.4	···	0.43	1.47	0.26	3.42	16
Tam 8	K5 III	2.33	2.7	0.3	1.16	3, 17
Tam 12	···	0.66	1.5	0.2	2.27	3
Tam 16	···	0.60	2.0	0.2	3.33	3
Tam 17	···	0.60	1.2	0.1	2.00	3

[a] If no spectral type is listed, type K5 III is assumed. In these cases, values of A_K contain an error of ∼0.2 mag due to uncertainty in assigned intrinsic color.

[b] Value of p_K estimated using values of $p_{\rm max}$, $\lambda_{\rm max}$, and K from Whittet et al. 1992. Fractional error (σ_{p_K}/p_K) taken equal to that of $\sigma_{p_{\rm max}}/p_{\rm max}$.

[c] Assumes $A_K = 0.56\lambda_{\rm max} E_{B-V}$.

References.—(1) Elias 1978; (2) Whittet et al. 1996; (3) Tamura et al. 1987; (4) Whittet et al. 1992; (5) Moneti et al. 1984; (6) Straižys & Meištas 1980; (7) Vrba & Rydgren 1985; (8) Kenyon et al. 1994; (9) Oja 1987; (10) SIMBAD database; (11) Crutcher 1985; (12) Straižys, Wisniewski, & Lebofsky 1982; (13) Ungerer et al. 1985; (14) Straižys, Černis, & Hayes 1985; (15) Slutskii, Stal'bovskii, & Shevchenko 1980; (16) Goodman et al. 1992; (17) Whittet et al. 1988.

outer layers of the cloud ($A_V < 3$ mag) appear to have optical properties similar to those in the diffuse ISM (Vrba & Rydgren 1985; Kenyon et al. 1994). In regions of higher density, infrared spectroscopy demonstrates the presence of icy mantles on the grains (Whittet et al. 1988, 1989; Chiar et al. 1995). The transition from bare to H_2O-mantled grains appears to occur at a rather well-defined value of $A_V = 3.3 \pm 0.1$ mag (the threshold extinction). Above this threshold value, the optical depth of the 3 μm ice feature (and hence the column density of H_2O on the grains) increases linearly with A_V. Solid CO demonstrates similar behavior, with a higher threshold extinction of $A_V \sim 6$ mag. Mantle growth represents a total change in grain surface properties, upon which some alignment mechanisms critically depend, and it is therefore of interest to compare p/A at extinctions above and below these thresholds.

2. OBSERVATIONAL DATA AND RESULTS

As compilations of visual polarization are heavily biased to low-extinction objects, observations in the K passband ($\lambda_0 = 2.2$ μm) offer a better opportunity to construct a homogeneous set of data covering stars with a wide range of extinctions. Values of p_K listed in Table 1 are adopted or deduced from published observations (Tamura et al. 1987; Goodman et al. 1992; Whittet et al. 1992, 1996). Note that the p_K-values of Whittet et al. (1992) were measured in a non-standard passband centered at 2.04 μm; standard p_K-values were determined using a power-law extrapolation of the observed $p(\lambda)$ at 1.64 and 2.04 μm from Whittet et al. (1992), except in four cases where the value at 2.04 μm was unknown. For the latter, the Serkowski formula

$$p/p_{\max} = \exp\left[-K \ln^2 (\lambda_{\max}/\lambda)\right] \quad (1)$$

(Serkowski et al. 1975) was used to deduce p_K. The parameters in equation (1), the peak polarization $p_{\max}$, the wavelength of maximum polarization $\lambda_{\max}$, and the width parameter K, were taken from Table 4 of Whittet et al. (1992). In all cases, data were rejected if the fractional error (σ_{p_K}/p_K) was greater than 20%.

Corresponding extinction data (A_K) are also listed in Table 1. In cases where the spectral type is known, visual and infrared photometry from the literature is used to derive infrared extinctions (A_K), assuming a standard extinction law: $A_K = 0.1A_V$, where $A_V = 1.1E_{V-K}$ (Whittet & van Breda 1978). In four cases lacking infrared photometry, we combine known values of $\lambda_{\max}$ and E_{B-V} (Whittet et al. 1996) with the relation $R_V = 5.6\lambda_{\max}$ (Whittet & van Breda 1978) to derive $A_K = 0.56\lambda_{\max}E_{B-V}$ (see Table 1), where $R_V = A_V/E_{B-V}$ is the ratio of total to selective extinction. In cases where the spectral type is unknown (as in Tamura et al. 1987 and Goodman et al. 1992), a spectral type of K5 III and an intrinsic color of $(J-K)_0 = 0.95 \pm 0.4$ are assumed. This spectral type corresponds to the mean of the Elias (1978) field stars, where the error in intrinsic color reflects the range in $(J-K)_0$ from types K0 III through M8 III (the span of the Elias 1978 set). Intrinsic colors are taken from Bessell & Brett (1988). Stars with the highest extinctions lack visual photometry, and in these cases we use an empirical formula for extinction based upon the infrared color excess E_{J-K}. Whittet (1992) showed that $A_V = rhr\ E_{J-K}$, where $r \approx 2.332/(0.778 - 1.164R_V^{-1})$, and with a mean value of $R_V \approx 3.1$ for the Taurus dark cloud (Whittet et al. 1996), we have $r \approx 5.8$, and thus $A_K \approx 0.58E_{J-K}$.

In Figure 1 we plot p_K/A_K versus A_K for all stars listed in Table 1. There is a clear trend of decreasing polarization efficiency with extinction, indicating that linear polarization of radiation due to aligned dust grains in the Taurus dark cloud is produced much more efficiently in regions of low extinction compared with more obscured lines of sight. This result is consistent with the findings of Goodman et al. (1995) for the cloud L1755. Similar but less dramatic trends have been observed previously in ρ Oph (Vrba, Coyne, & Tapia 1993), R CrA (Vrba, Coyne, & Tapia 1981), and Cha I (McGregor et al. 1994; Whittet et al. 1994). It may also be worth noting that analogous declines with extinction have been observed in the production efficiencies of the diffuse interstellar bands (Adamson, Whittet, & Duley 1992), although no direct relationship between their carriers and aligned dust grains has ever been established.

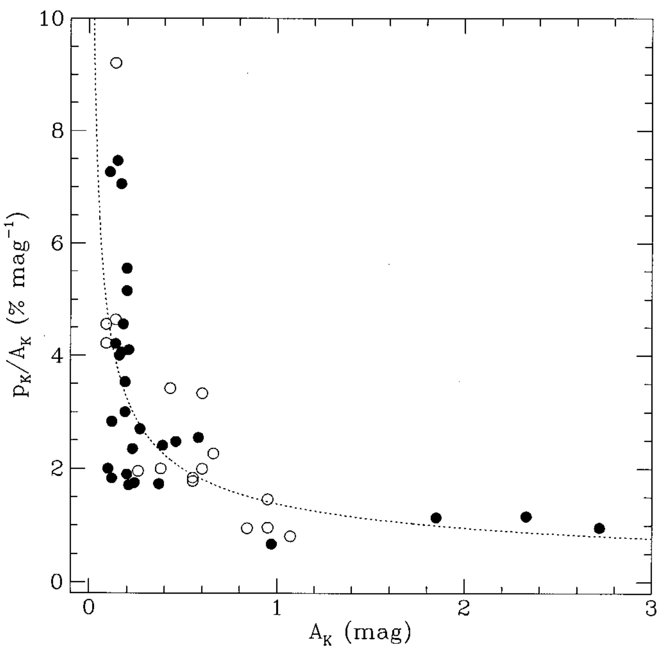

FIG. 1.—Plot of polarization efficiency p_K/A_K against extinction A_K, based on data from Table 1. Filled circles and open circles indicate stars with known and assumed spectral types, respectively (see § 2). The dotted line represents an unweighted least-squares power-law fit to all data points ($p_K/A_K = 1.38A_K^{-0.56}$).

3. DISCUSSION

3.1. *Power-Law Representation*

The trend in the data plotted in Figure 1 is well matched by a power law $p_K/A_K \propto A_K^{-\alpha}$ for some index α. Tamura et al. (1987) and Goodman et al. (1992) previously applied this form to subsets of our current database. A least-squares fit to all points in the corresponding p versus A diagram yields

$$p_K/A_K = (1.38 \pm 0.34)\, A_K^{-0.56 \pm 0.17}\%\ \mathrm{mag}^{-1}. \quad (2)$$

This form is plotted in Figure 1. Several physical processes may contribute to this dependence of alignment on extinction; some possibilities are discussed below. Our aim is to stimulate further work on the interpretation of our observational result, in order to better understand the alignment mechanism.

3.2. *Density Dependence for DG Alignment*

If we assume paramagnetic alignment of spheroids of constant size by the classical DG mechanism, operating under conditions of constant gas (T_g) and dust (T_d) temperatures ($T_g \neq T_d$), we may easily show that (Vrba et al. 1981, 1993)

$$p/A = cB^2/n, \quad (3)$$

where B is the magnetic field strength, n is the gas density, and c is a constant. This approach predicts the observed dependence of p/A on A: assuming a density dependence for B of the form $B \propto n^{\kappa}$, where $\frac{1}{3} < \kappa < \frac{1}{2}$ (Mouschovias 1978), we have $p/A \propto n^{2\kappa - 1}$; since $n = N/L$ (where N is the column density and L is the length of the column), and as it is known from observations that $A \propto N(\mathrm{H})$, we deduce that $p/A \propto A^{2\kappa-1}$, which is the same functional form as equation (2). However, there are problems associated with this approach. Relevant effects such as the existence of small-scale inhomogeneities in the magnetic field and the coupling of gas and dust temperatures in regions of high density have been ignored (see below). Moreover, classical DG alignment cannot give the correct wavelength dependence of interstellar polarization unless the grains are superparamagnetic so that the probability of alignment is a strong function of their size (Mathis 1986). The simple model developed by Vrba et al. (1981, 1993) does not take into account recent developments in DG alignment theory (Roberge, DeGraff, & Flaherty 1993; Lazarian 1995a, b). In fact, it can be shown that equation (3) is only valid over a restricted range of physical conditions (such that $\delta \ll 1$, where δ is the ratio of gaseous and magnetic damping times; see Roberge et al. 1993).

3.3. *Temperature*

The assumption of constant, unequal gas and dust temperatures must ultimately fail because they approach each other ($T_g \rightarrow T_d$) in the cores of molecular clouds. It can be shown by use of general expressions derived by Lazarian (1995b) that, in this situation, $p/A \propto (T_g - T_d)/T_g$ for DG alignment, and thus the coupling of gas and dust temperatures will in itself lead to a monotonic decline in alignment with density in the cloud cores. Whether this is an important factor over the range of densities sampled by our observations is difficult to determine.

3.4. *Magnetic Field Structure*

We have assumed throughout that the magnetic field has a uniform morphology. However, even if this is true to a good approximation on the scale of the complex as a whole, it is perhaps unlikely to be true on the smallest scales. Indeed, the contemporary picture of clouds as "clumps within clumps" (see Scalo 1987; Elmegreen 1992) proposes a rather complex internal structure for the magnetic field in molecular clouds. Jones (1989) and Jones, Klebe, & Dickey (1992) have shown that the observed trend in polarization with extinction over many lines of sight may be modeled in terms of a magnetic field with distinct random and uniform components. This treatment predicts $p \propto \tau^{0.5}$ (Jones 1989), i.e., $p/A \propto A^{-0.5}$, which is in fact close to the observed dependence (Fig. 1); however, we caution that the Jones model may not be applicable to individual clouds.

3.5. *Grain Shape*

Enhancements of R_V and $\lambda_{\max}$ toward the inner regions of dark clouds (Whittet & Blades 1980) and the detection of icy mantles (Whittet et al. 1988) indicate grain growth by coagulation and mantle condensation. One consequence of these processes may be to produce grains that are more closely spherical, alignment of which would naturally lead to lower values of p/A (Purcell & Spitzer 1971; Aannestad & Purcell 1973). The importance of this effect in our data is difficult to quantify.

3.6. *Suprathermal Spin*

It is well known that grain surfaces are active sites for the formation of H_2. Binding energy released by this process may be transferred in part to the grain as rotational kinetic energy. H_2 formation is likely to occur at preferential sites on the surface (Hollenbach & Salpeter 1971), and this may lead to angular velocities a factor of $\sim 10^5$ higher than those predicted by random elastic gas-grain collisions (Purcell 1975, 1979). This effect may lead to very efficient alignment of the grains, but the necessary physical conditions may not be available in all environments. In dense regions, $H \rightarrow H_2$ conversion may be essentially complete and recombination events rare (Savage et al. 1977), although Lazarian (1995c) concluded that H/H_2 fractions as low as 10^{-2}–10^{-3} may be sufficient to drive suprathermal rotation in dark clouds. Another important factor is the resurfacing of the grains by mantle growth. H adsorption sites on an icy surface are weaker than those available on a bare silicate or carbonaceous surface. Hence, the time a hydrogen atom spends on an H_2O surface (and thus the probability that it will recombine) will be smaller than on a bare, unmantled grain (Tielens & Allamandola 1987; Williams 1993). Changes in grain surface properties associated with the observed appearance of H_2O mantles ($A_K > 0.3$ mag) and CO mantles ($A_K > 0.6$ mag) do not have an obvious effect on the polarization efficiency within the scatter of our data (Fig. 1), in the sense that no major discontinuities are seen near these values of extinction. It may be that the presence (or absence) of mantles has little effect on the ability of a grain to align in the ambient magnetic field; this would be consistent with the observed presence of polarization enhancement in the 3 μm ice feature (Hough et al. 1988), demonstrating that grains mantled with H_2O ice do, indeed, align to some degree.

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