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ON THE INTERPRETATION OF POLARIZATION MAPS OF YOUNG STELLAR OBJECTS

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ABSTRACT

Polarization maps obtained during the past few years of regions around young stellar objects associated with optical jets and/or bipolar outflows and/or cometary nebulae show, in many cases, a centrosymmetric pattern usually attributed to scattering of radiation from the central sources by dust grains in their vicinity. In other cases, a pattern of aligned polarization vectors is observed close to the central object; dichroic extinction by aligned grains has been proposed for their interpretation. This paper explores different ways to explain such a pattern without invoking aligned grains. We find that multiple scattering alone with an optically thick disk and optically thin polar lobes can explain most, if not all, of the polarization maps so far observed. If this interpretation is correct, aligned grains and magnetic fields are no longer required. However, this does not disprove the presence of magnetic fields around young stars; it only shows that they are not efficient at aligning grains in the circumstellar environment of pre–main-sequence stars.

Subject headings: polarization — stars: circumstellar shells — stars: pre–main-sequence

I. INTRODUCTION

Polarization maps of regions around various young stellar objects have been obtained recently. Very often, the pattern described by the polarization vectors (as given by the electric vectors) is a pattern which has been called centrosymmetric. If one traces perpendiculars to the polarization vectors, they point toward the central illuminating source. Such a pattern is easily explained by single scattering since, in that case, the polarization vector is usually (always, if the scatterer is an electron) perpendicular to the scattering plane.

However, for some sources, a different behavior can be observed close to the source: the vectors are more or less aligned along a given direction; this direction is usually perpendicular to the direction of the mass outflow from the central source. The usual interpretation for those peculiar patterns is one of dichroic extinction by aligned grains in a circumstellar disk (see, e.g., the arguments given by Wolstencroft 1985). Many mechanisms can, in principle, align grains. The one suggested most of the time is magnetic alignment. The magnetic field is frozen into the matter and acquires an essentially toroidal geometry due to strong rotational torques in the disk following the scenario given by Mestel and Paris (1984).

The sources for which polarization maps have been published are listed in Table 1. The polarization patterns are classified in column (2) into centrosymmetric (cs), aligned vectors (av) and peculiar (pec). The third column gives the central wavelengths of the bandpasses used for obtaining the maps; column (4) answers the question, Is the central source visible? In fact, all sources show a centrosymmetric pattern in at least part of their regions, and some of them show a region, usually near the central source, where the polarization vectors are more or less aligned. If aligned vectors are observed in part of the map, the object is assigned to the "av" category, even though the polarization vectors are centrosymmetric in the rest of the map.

In a summarizing paper on polarization, jets, and the distribution of the circumstellar dust around young stellar objects, Bastien (1987) considered two different types of models: (1) scattering by spherical dust grains distributed in an axially symmetric, but otherwise arbitrary, configuration, (2) dichroic extinction by nonspherical grains aligned in some preferred direction. For models of type 1, prolate configurations for the scattering grains in the optical were preferred. These models are also compatible with a disk of dust grains, optically thick in the visible, which is responsible for the polarization in the near-infrared, where the grains in the lobes have essentially no effect. For models of type 2, the grains have to be aligned preferentially perpendicular to the plane of the disk in order to explain the fact that the polarization measured in a diaphragm centered on the source is usually (in more than 60% of the sources) perpendicular to the outflow axis. If the alignment is by a magnetic field, then the field has to be mostly in the plane of the disk or at least leave the disk at an angle $<45°$ if one assumes that the alignment is due to the Davis-Greenstein mechanism. This seems to contradict recent models where the magnetic field was perpendicular or mostly perpendicular to the disk (Pudritz 1985; Uchida and Shibata 1985*a*, *b*).

A table (Table 5) in Bastien (1987) summarizes the arguments for and against both types of models. There are many arguments against models with aligned grains, which clearly implies that these models are not applicable at least to some sources where scattering is required. On the other hand, there was only one argument against scattering models, namely that they could not explain the polarization maps with aligned polarization vectors. This led Bastien (1987) to conclude that both types of models (scattering and aligned grain) were required to explain all sources.

Circular polarization has been detected in three out of five T Tauri stars recently (Nadeau and Bastien 1986). These observations can easily be explained by multiple scattering, and also with aligned grains. They offer no hope in deciding between the two models without detailed modeling and comparison with the data.

In this paper, we question the interpretation of some polarization maps as being produced by aligned grains. We propose instead that these maps can be explained by scattering only, given the appropriate geometry. In § II we examine three different ways of obtaining polarization vectors which are not

TABLE 1

POLARIZATION MAPS OF GALACTIC SOURCES

Object (1)	Polarization Pattern[a] (2)	λ (μm) (3)	Central Source Visible[b] (4)	References (5)
NS 3	cs	0.85	yes	1
W3 IRS 1, 2	av	2.2	IR	2
FS Tau (Haro 6-5B)	av	0.65, 0.75	no	3, 4, 5
LkHα 101/NGC 1579	cs	0.65	yes	6
L1551 IRS 5	av	0.85	no	7, 4, 5
	av	1.0	...	8
BN/KL	av	2.2	IR	9
	cs	3.8	...	10
IRAS 05329−0505	av	0.8	IR	11
VLA1/HH 1, 2, NGC 1999	av	0.85	no	5, 12
Horsehead nebula/B33	pec	0.85	pec	13
NGC 2071 IR	note	2.2	IR	2
LkHα 208	cs	0.55	yes	14
R Mon/NGC 2261	av	0.55, 0.7	yes	15
		0.48, 0.55, 0.65	...	16
NGC 2264	av	2.2	no	2
NS 14	av	0.85	no?	1
OH 0739−14	av	2.2	yes	17
Bruck "bipolar nebula"	cs	0.75	yes	18
M2-9	av	0.46, 0.76, 0.85	IR	19
GGD27 IRS	cs	2.2, 3.5	IR	20
Serpens nebula	av	0.7	yes	21, 22
R CrA	av	0.65	yes	23
T CrA	av	0.65	yes	23
Parsamyan 21	av	0.85	yes	24
S106	cs	2.2	yes	25
GL 2591	cs	1.0	IR	8
LkHα 233	av	0.46, 0.54, 0.76	yes	26
PV Cep	av	0.78	yes	5
V645 Cyg (GL 2789)	av	1.0	yes	8
NGC 7129 (RNO 138)	cs	0.85	no	27
S140 IRS (GL 2884)	cs	2.2	no	28, 29
Cep A/GGD 37	cs	2.2	no	28
	cs	3.8	no	29
S158 IRS 4 (in NGC 7538)	pec	2.2	no	2

[a] Meaning of abbreviations: cs, centrosymmetric; av, aligned vectors; pec, peculiar, refer to the notes on individual sources; note, see notes on individual sources.

[b] In this column, IR means that the source is detected in the infrared only, not at visible wavelengths.

NOTES.—BN/KL: OMC-1 which contains the Becklin-Neugebauer/Kleinmann-Low infrared region is quite complex. Near IRC 2, Hough *et al.* 1986 favor superparamagnetic grains or grains aligned by a magnetic field larger than in the general interstellar medium to explain the polarization pattern in the molecular hydrogen emission line at 2.2 μm. They suggest that this mechanism is dominated by scattering at 3.8 μm.

Horsehead Nebula: This region is illuminated by a distant star, σ Ori. Warren-Smith, Gledhill, and Scarrott (1985) also suggest the possible presence of aligned grains to explain their map.

NGC 2071 IR: The 2.2 μm map is consistent with a scattering mechanism. However, the map is not extended sufficiently to give it a definite pattern.

M2-9: This is a proto–planetary nebula.

S158 IRS 4: This object is probably a polarized reflection nebula illuminated by S158 IRS 5, a special case of a scattering mechanism with the exciting star not embedded in the nebula (Heckert and Zeilik 1984).

REFERENCES.—(1) Scarrott *et al.* 1986*a*; (2) Heckert and Zeilik 1984; (3) Gledhill, Warren-Smith, and Scarrott 1986; (4) Scarrott *et al.* 1985; (5) Scarrott *et al.* 1986*b*; (6) Redman *et al.* 1986; (7) Draper, Warren-Smith, and Scarrott 1985*c*; (8) Lenzen 1987; (9) Hough *et al.* 1986; (10) Werner, Dinerstein, and Capps 1983; (11) Wolstencroft *et al.* 1986; (12) Strom *et al.* 1985; (13) Warren-Smith, Gledhill, and Scarrott 1985; (14) Shirt, Warren-Smith, and Scarrott 1983; (15) Gething *et al.* 1982; (16) Aspin, McLean, and Coyne 1985; (17) Heckert and Zeilik 1983; (18) Scarrott *et al.* 1987; (19) Aspin and McLean 1984; (20) Yamashita *et al.* 1987; (21) King, Scarrott, and Taylor 1983; (22) Worden and Grasdalen 1974; (23) Ward-Thompson *et al.* 1985; (24) Draper, Warren-Smith, and Scarrott 1985*a*; (25) McLean *et al.* 1987; (26) Aspin, McLean, and McCaughrean 1985; (27) Draper, Warren-Smith, and Scarrott 1985*b*; (28) Joyce and Simon 1986; (29) Lenzen, Hodapp, and Solf 1984.

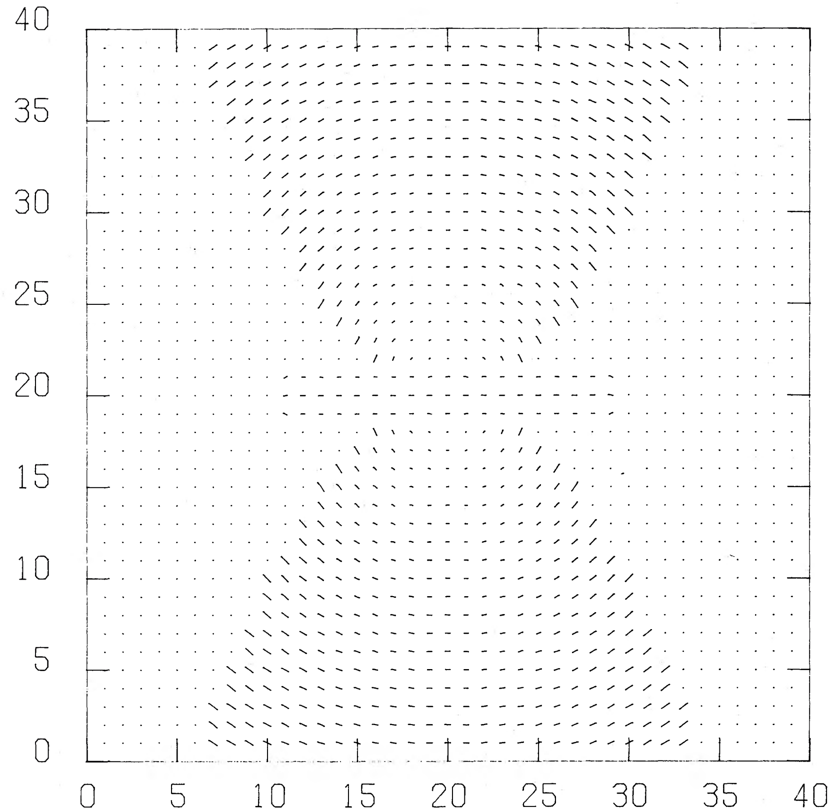

FIG. 1.—Polarization map computed with Mie scattering. There are two regions: (1) a region with single scattering on the surface of two paraboloids which are on both sides of (2) an optically thick disk seen edge-on ($i = 90°$) with multiple scattering as described in the text. The disk is clearly distinguishable by its characteristic pattern of aligned polarization vectors. The maximum polarization in the disk is 25%, while it is 99% in the parabolic lobes.

perpendicular to the scattering plane, hence which can be expected to yield polarization maps which will not be centrosymmetric. We find that one of them can reproduce adequately the observations.

II. WAYS OF PRODUCING POLARIZATION THAT IS NOT PERPENDICULAR TO THE SCATTERING PLANE

In the investigation of alternate mechanisms for explaining the patterns of aligned polarization vectors, we considered three possibilities to get a linear polarization which is not perpendicular to the scattering plane; two of them were unsuccessful:

1. *Dielectric Spheres.*—If the grain material is such that the imaginary part of its refractive index is zero or very small, such as is the case for small dielectric spheres, a polarization reversal (i.e., polarization parallel to the scattering plane) can be obtained if $x = 2\pi a/\lambda \gtrsim 1.89$ (for an index of refraction = $1.65 - 0.0j$). This case was discussed by Bastien (1987) for sources measured through a diaphragm. However, the polarization vectors would all be radial from the central source, which is not observed.

2. *Cometary Grains.*—Polarization observations of comets have shown that the grains in all comets have similar optical properties (e.g., Bastien, Ménard, and Nadeau 1986 and references therein). A polarization parallel to the scattering plane is observed when the phase angle (the angle Sun-comet-Earth) is smaller than a critical value $\approx 20°$. Polarization maps computed with such a polarization law do not reproduce the observations.

A third possibility for producing polarization vectors that are not perpendicular to the radius vector from the star is to have multiple scattering. We first consider an optically thick disk seen edge-on, $i = 90°$ (the inclined disk is considered below). No light from the central source can pass through the disk and reach the observer directly. However, the observer can still detect radiation at the position of the central source; this radiation is multiply scattered light, scattered first on both sides of the disk and then on the near side of the disk. A polarization map has been computed for such an optically thick disk. The light in front of the disk comes from the star, goes to first scatterers distributed in two planes on both sides of the disk, and then goes to scatterers on the near edge of the disk. In addition, for the outflow region on both sides of the disk, the polarization has been computed with single scattering on the sides of two parabolas of revolution. Accurate Mie scattering by spherical grains has been used for calculating the scattering in the disk and in the paraboloids. The results are shown in Figure 1. One can clearly see a band of aligned polarization vectors in the disk; the polarization can reach 25% there. The pattern of vectors is quite insensitive to the exact location of the first scatterers, as long as they are not located in the central plane of the disk (which yields polarization vectors perpendicular to the disk) but rather on both sides of it.

We now consider an inclined disk. Figure 2 displays the results for a flat disk inclined at 60°. There are also two paraboloids as described above, inclined by the same angle. Double scattering is used for computing the polarization in the disk.

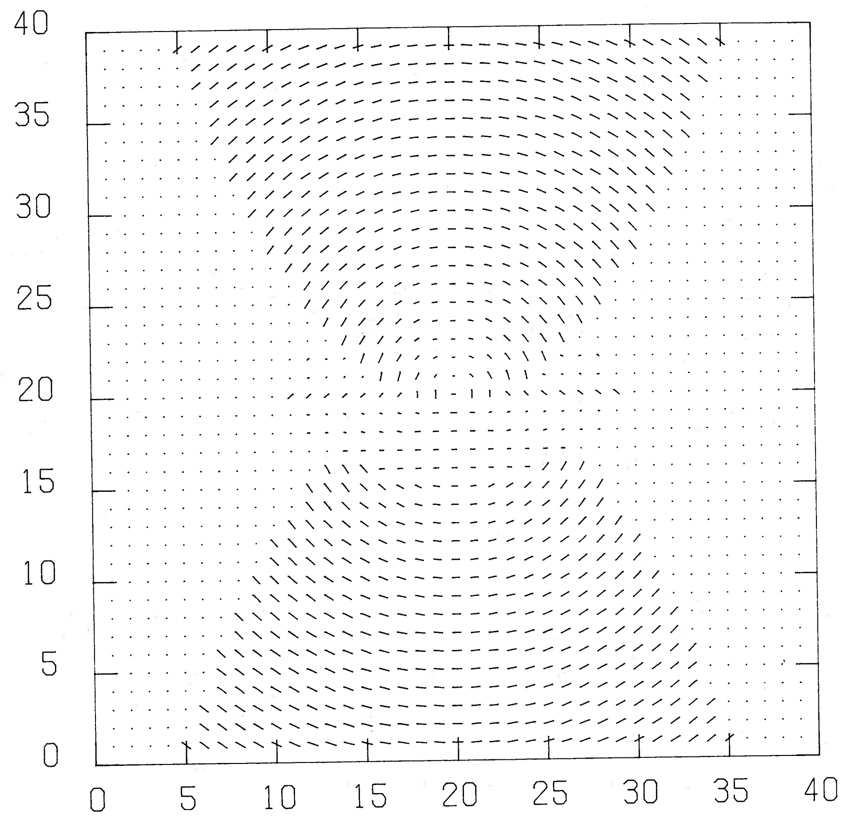

FIG. 2.—Similar to Fig. 1 but for a disk inclined at 60°. The computation of the multiple scattering in the disk is described in the text. The disk is not visible "through" the upper paraboloid when it is behind it from the observer's point of view. The polarization is a bit lower than in Fig. 1. The disk shows 21% and the lobes 62%.

The first scatterers are located in an array parallel to the plane of disk, but above it and centered on the point of interest. A similar pattern of aligned polarization vectors is obtained. One can obtain such a pattern for inclinations as low as 40°.

We now justify the location of the first scatterers used above. The justification is based on the fact that the optical depth in the vicinity of the disk is very dependent on direction. If the optical depth parallel to the plane decreases very rapidly with height above (or below) it, then a location in the disk at some distance from the star is expected to be illuminated mostly by scattered light from above (or below). This is where we have put the first scatterers for the inclined disk.

III. DISCUSSION

We have thus far shown that multiple scattering can explain the polarization maps. We now argue that aligned grains cannot explain them. There are the difficulties already mentioned in Bastien (1987, his Table 5): (1) the correlation between polarization and brightness variations observed for RY Lup (Bastien *et al.* 1988); (2) the various wavelength dependences of the polarization observed in T Tauri stars that cannot be explained by extinction by aligned grains; (3) the polarization reversals as a function of wavelength; (4) the large ($\Delta P > 1\%$ and/or $\Delta\theta > 30°$) and rapid ($\Delta t < 1$–3 days) polarization variations observed in some T Tauri stars that are difficult to explain with aligned grains.

In addition, the magnitude of the polarization, 10%–15%, when aligned grains are presumed to cause it, requires very efficient alignment mechanisms. We point out that not even one of the numerous papers presenting polarization maps with a pattern of aligned vectors has addressed the question of how the magnitude of linear polarization can be explained with aligned grains. The polarization in regions where aligned vectors are observed typically reaches 10%–15%, and, in one object (V645 Cyg), 30% is detected.

Finally, comparison of polarization observations of four objects at 1 and 2.1 μm led Lenzen (1987) to exclude aligned grains as a possible explanation for polarization maps.

The polarization maps presented above can indeed explain the observations. Recently, Yamashita *et al.* (1987) attempted to compute polarization by single Mie scattering at the surface of an inclined paraboloid, as we did above in § II*c*, and succeeded in explaining the observed centrosymmetric map of GGD 27 IRS. The results presented above illustrate the effects to be expected from multiple scattering in a geometry appropriate for the environment of young stellar objects. Such a geometry, with an optically thick disk and low-density polar lobes seems to be quite common. Therefore, our results apply to other objects with similar disk structures. Such a structure is not new. For example, it was used by Elsässer and Staude (1978) to explain the polarization observations of the BN object made through a single diaphragm centered on the object. An effect similar to that reported here—polarization parallel to an optically thick surface—was found by Angel (1969)[1] in a very different context. Our calculations are crude:

[1] We are indebted to G. D. Schmidt for bringing this reference to our attention.

we considered two regions, one with single scattering only and the other with double scattering only. The treatment of the boundary between these two regions—disk and paraboloids—leaves much to be desired. It is clear that a full treatment of the radiative transfer problem is required Detailed multiple scattering calculations are currently underway (Ménard and Bastien 1988) and are expected to confirm our results.

As a consequence, single and multiple scattering alone can explain all the polarization properties so far observed in young stellar objects. There is no need to invoke elongated grains aligned by some mechanism, for example a magnetic field. In fact, the alignment mechanisms have difficulties in explaining the high polarizations observed. However, these results do not imply that magnetic fields around young stellar objects are negligible. They simply mean that magnetic fields are not efficient at aligning grains in such an environment which is highly active dynamically.

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