POLARIZATION OF BACKGROUND STARLIGHT AND THE STRUCTURE OF THE INTERSTELLAR MAGNETIC FIELD

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1. Abstract/Introduction

We discuss the use of polarization maps of background starlight in studying the structure of the interstellar magnetic field. We make the assumption that the polarization observed is due to magnetically aligned dust grains associated with interstellar clouds along the line of sight, and that the position angle (Θ_E) of polarization observed gives the direction (modulo 180°) of $\vec{B}_\perp$, the plane-of-the-sky projection of the (line-of-sight-averaged) magnetic field.

There are two basic points in this paper. (1.) Out of context, the projected orientation of an elongated dark cloud may appear special (e.g. roughly "parallel" or "perpendicular") in relation to the local (plane-of-the-sky) field direction given by polarization observations, but, when the view is expanded to include an entire complex of dark clouds, the shape and orientation of clouds within a complex often appears unrelated to the field structure. (2.) The dispersion in the postion angle of polarization observed in a region of the sky contains information about the ratio of the strength of the uniform (straight) component of the local magnetic field as compared to the dispersion (nonuniform component) in the field. Furthermore, in a region where Zeeman measurements covering the same region as polarization observations have been made, the uniform-to-nonuniform ratio deduced for the field from polarization data, can be combined with information about the line-of-sight field and an estimate of the correlation length of the field, to describe the magnetic field in three dimensions. We discuss the results of such an analysis for the dark cloud Lynds 204 (L204).

Keywords : Magnetic fields, dark clouds, L204

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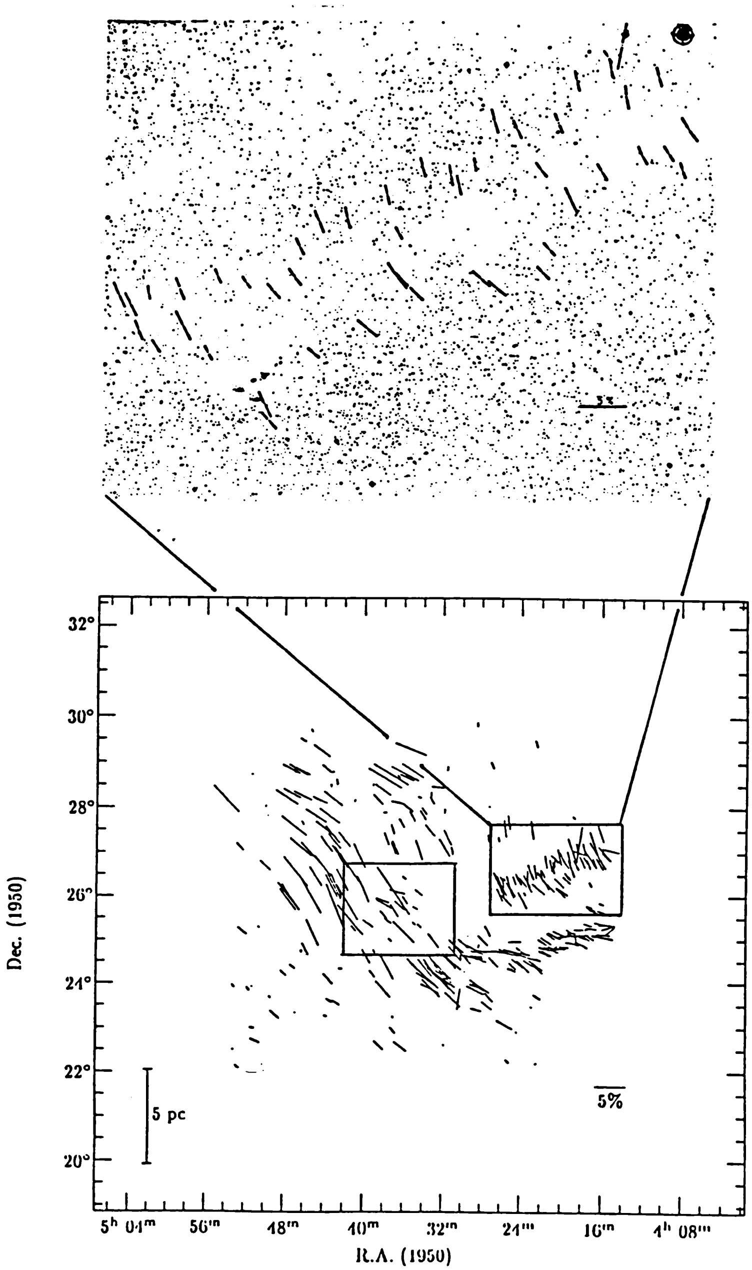

Figure 1 : *Upper Panel–* Optical polarization of background starlight in the B216-217 dark cloud region, superposed on a reproduction of the Palomar Sky Survey photograph (Heyer *et al.* 1987). *Lower Panel–* Optical polarization map of the Taurus molecular cloud complex (Moneti *et al.* 1984; Heyer *et al.* 1987; Goodman *et al.* 1990). The boxed region not enlarged above shows the Heiles Cloud 2 area studied (at 2 μm) by Tamura *et al.* 1987.

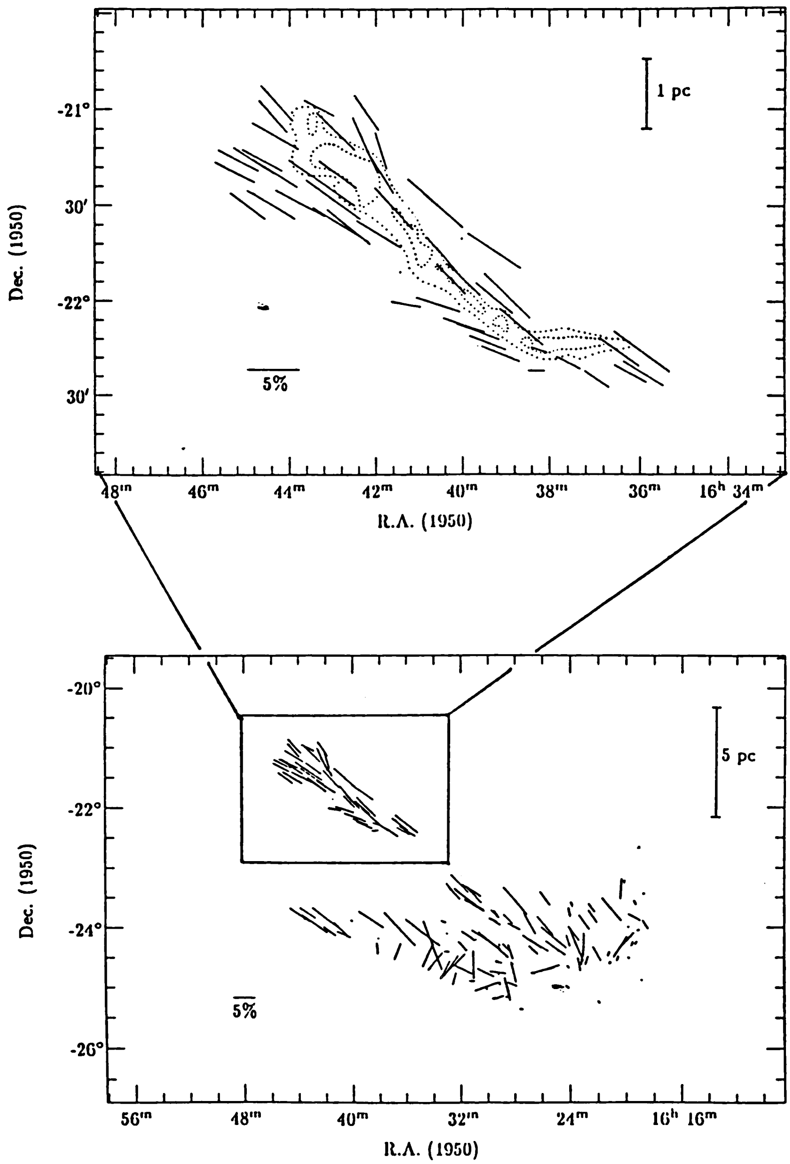

Figure 2 : *Upper Panel*– Optical polarization of background starlight in the L1755 dark cloud region (Goodman *et al.* 1990), superposed on a ^{13}CO contour map (Loren 1989). *Lower Panel*– Optical polarization map of the Ophiuchus molecular cloud complex (Vrba, Strom, and Strom 1976; Goodman *et al.* 1990).

2. Orientation of Cloud Features with Respect to $\vec{B}_\perp$

To date, one of the most prevalent uses of polarization maps of the regions around dark clouds has been to directly compare the projected magnetic field structure with the projected cloud structure (e.g. a molecular-line map). When one elongated cloud is examined alone, out of the context of the surrounding cloud complex, often one is led to believe that the cloud axis is oriented in a special way with respect to the field. Figures 1 and 2 illustrate this point. Based on the top panel of Figure 1 (B216-217) alone, we might deduce that filaments are elongated perpendicular to field lines : while, based on the top panel of Figure 2 (L1755) alone, we would come to an "orthogonal" conclusion–that elongation is parallel to field lines. In truth, in most cases, the orientation of a filament is, when viewed alone, arbitrary with respect to $\vec{B}_\perp$. However, when we expand our view to include an entire cloud complex, we find that the field has a smooth structure on scales of at least tens of pc, and that the orientation of several-pc-long filaments within the complex is not necessarily obviously governed by the structure of the magnetic field. The lower panels of Figures 1 and 2 show polarization maps of the entire Taurus and Ophiuchus molecular cloud complexes, respectively, and it is apparent from these maps that the "special" orientation of B216-217 and/or L1755 with respect to the magnetic field, could be fortuitous.

It is important, also, to keep in mind that the orientations we observe on the plane of the sky represent projections of true orientations in three-dimensional space. The probability distribution for the true angle between two directions in space, given an observed projected (2D) angle, is only weakly peaked at the true (3D) angle, with a long tail extending to larger values, and a small chance that the 2D angle observed is actually greater than the true 3D angle. Given the relatively large number of filamentary clouds for which there are polarization maps (~ 10), and given that they show relatively random orientation of cloud axis with respect to $\vec{B}_\perp$, it is safe to assume that the true 3D angle between a filament and the field is likely to be larger than the 2D angle observed.

3. Analysis of the Dispersion in Polarization Angle

Given that the direct (i.e. morphological) interpretation of polarization maps is apparently less than straightforward–especially concerning the relation between the field direction and the elongation of filamentary clouds, we may perhaps wish to extract information about the magnetic field from polarization data in less direct, but more quantitative, ways.

What polarization maps definitely show is a tremendous degree of coherence or "uniformity" in the structure of the interstellar magnetic field. In other words, if one plots the number distribution of polarization angle over a given region, the dispersion in the distribution is small. Just how large a region will still show a small dispersion is a question which must at least partially concern the correlation length of the field. We know, however, that even over an entire molecular cloud complex, such as Taurus (see Figure 1, lower panel), the distribution of $\Theta_{\rm E}$ remains relatively narrowly peaked (Goodman *et al.* 1990; Myers and Goodman 1990).

Myers and Goodman (1990; hereafter MG90) describe a method by which the observed distribution of $\Theta_{\rm E}$ is modelled as arising from the sum of a uniform (straight) field plus a nonuniform field characterized by a one-dimensional dispersion σ_B.[1] We refer the reader to MG90 for a detailed description of this model, and we will present only the results here.

The MG90 model fits observed distributions of polarization angle in terms of two parameters : the mean polarization angle $\bar{\Theta}_{\rm E}$, and the dispersion $s = \frac{\sigma_B}{N^{\frac{1}{2}} B_{ox}}$, where N is the number of correlation lengths along the line of sight through the cloud, and B_{ox} represents the plane-of-the-sky component of the uniform magnetic field. An example of the model fit to the distribution of polarization angle for the dark cloud L204 is illustrated in Figure 3a. (MG90 presents similar fits for 14 other dark clouds, five cluster regions, and six dark cloud complexes.) For the fit shown in Figure 3a, $\bar{\Theta}_{\rm E} = 70 \pm 2°$ and $s = 0.44 \pm 0.02$.

If several Zeeman measurements have also been made in a region where optical polarization data is available, the line-of-sight field information provided by the Zeeman data can be combined with the value of $\bar{\Theta}_{\rm E}$ and s from a fit to the distribution of polarization angle, to estimate the three-dimensional uniform field component, and its inclination to the line-of-sight. In L204, Heiles (1988), has made Zeeman measurements on a grid of 27 positions covering approximately the same region of the sky as the McCutcheon *et al.* (1986) polarization measurements used to construct the distribution in Figure 3a (see Figure 3b). MG90 combine the polarization and Zeeman data to find a uniform field in L204 of 6 μG, inclined at 47° to the line of sight, projected along the line 70° E of N in the plane of the sky.

4. Discussion : For the Future

Since one must still be able to "see" a star through the gas along the line of sight in order to make an optical polarization observation, the information from optical polarization maps technically only pertains to gas with column density less than 2×10^{21} cm^{-2}, corresponding to about 2 mag A_V, or the periphery of a dark cloud. It is possible that the structure of the field traced by optical polarization observations is not representative of the denser gas associated with the visually opaque portions of a dark cloud.

Existing infrared polarization observations, which can observe stars through far more extinction than optical observations, would seem to indicate that the field structure in higher density regions is not markedly different than what is found optically. For example, in the Heiles Cloud 2 region (marked by a box in the lower panel of Figure 1), Tamura *et al.* (1987) find a similar direction and dispersion in

[1] Chandrasekhar and Fermi (1953), Jokipii and Parker (1969), and Zweibel (1990) also present relevant analyses of the disperion in the interstellar magnetic field.

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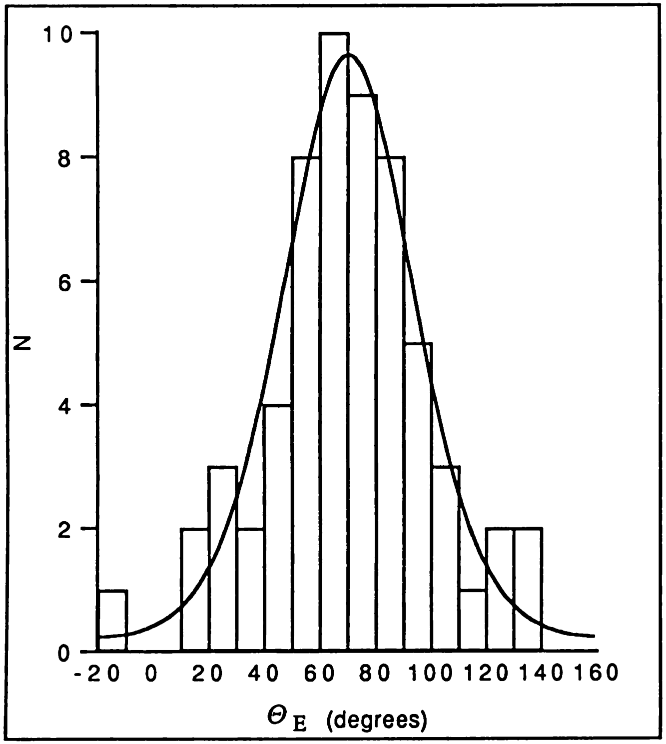

L204

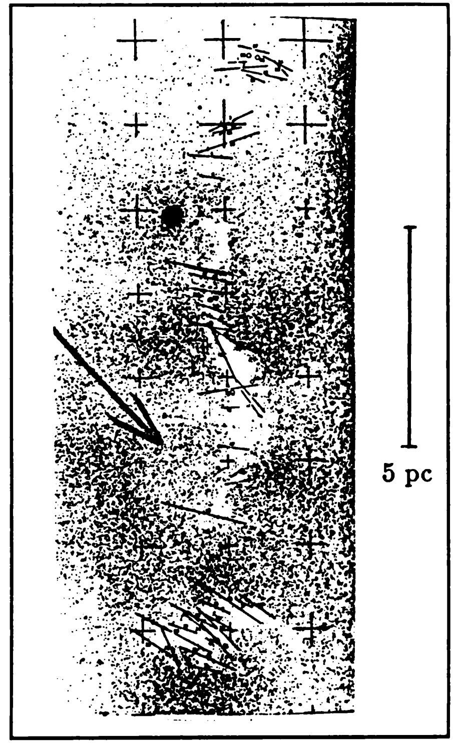

Figure 3a

Figure 3b

Figure 3 : *(a.)* The distribution of polarization position angle, Θ_E for the dark cloud L204, based on the data shown in *(b.)* optical polarization of background starlight in the L204 dark cloud region (McCutcheon *et al.* 1986), and HI Zeeman measurements (Heiles 1988), indicated by crosses with size proportional to the line-of-sight field strength superposed on an optical photograph. (Figure 3b is reproduced from Heiles 1988.)

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the field as measured by 2 μm polarization observations to what is indicated by the Moneti *et al.* (1984) (optical) data shown in Figure 1.

More infrared polarization data is necessary before we can say, with statistical evidence, what changes take place in the nature of the field over a range of densities.

References

Chandrasekhar, S. and Fermi, E. : 1953, "Problems of Gravitational Instability in the Presence of a Magnetic Field." *Ap. J.*, **118**, 113.

Goodman, A.A., Bastien, P., Myers, P.C., and Ménard, F. : 1990, "Optical Polarization Maps of Star Forming Regions in Perseus, Taurus, and Ophiuchus." *Ap. J.*, **359**, 363.

Heiles, C. : 1988, "L204 : A Gravitationally Confined Dark Cloud in a Strong Magnetic Environment." *Ap. J.*, **324**, 321.

Heyer, M.H., Vrba, F.J., Snell, R.L., Schloerb, F.P., Strom, S.E., Goldsmith, P.F. and Strom, K.M. : 1987, "The Magnetic Evolution of the Taurus Molecular Clouds I. Large Scale Properties." *Ap. J.*, **321**, 855.

Jokipii, J.R., and Parker, E.N. : 1969, "Stochastic Aspects of Magnetic Lines of Force with Application to Cosmic-Ray Propagation." *Ap. J.*, **155**, 799.

Loren, R.B. : 1989, "The Cobwebs of Ophiuchus. I. Strands of ^{13}CO : The Mass Distribution." *Ap. J.*, **338**, 902.

McCutcheon, W.H., Vrba, F.J., Dickman, R.L., and Clemens, D.P. : 1986, "The Lynds 204 Complex : Magnetic Field Controlled Evolution?" *Ap. J.*, **309**, 619.

Moneti, A., Pipher, J.L., Helfer, H.L., McMillan, R.S., and Perry, M.L. : 1984, "Magnetic Field Structure in the Taurus Dark Cloud." *Ap. J.*, **282**, 508.

Myers, P.C. and Goodman, A.A. : 1990, "On the Dispersion in Direction of Interstellar Polarization." submitted to *Ap. J.*.

Tamura, M., Nagata, T., Sato, S., and Tanaka, M. : 1987, "Infrared polarimetry of dark clouds–I. Magnetic field structure in Heiles Cloud 2." *M. N. R. A. S.*, **224**, 413.

Vrba, F.J., Strom, S.E., and Strom, K.M. : 1976, "Magnetic Field Structure in the Vicinity of Five Dark Cloud Complexes." *A.J.*, **81**, 958.

Zweibel, E. : 1990, "Magnetic Fieldline Tangling and Polarization Measurements in Clumpy Molecular Gas." submitted to *Ap. J.*.