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The Magnetic Field in L1 457, Multiband Photopolarimetry

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Abstract

We have performed multiband photopolarimetry towards stars behind the molecular cloud L1 457 (MBM 12). This cloud is the nearest known molecular cloud (65pc) and is thought to be contained within the local "hot bubble". The polarization shows a regular structure indicating that the cloud is threaded by an ordered magnetic field. The wavelength dependence of the polarization seems to indicate that the grains in L1 457 have higher indices of refraction than normal for interstellar clouds. However, the wavelength of maximum polarization indicates that their size distribution is close to normal.

1. Introduction

Starlight is often polarized by its passage through interstellar material (Whittet, 1992). This polarization is generally considered to be due to the alignment of elongated dust grains by the interstellar magnetic field. Several mechanisms for the alignment have been proposed but the most probable one is some modification of the Davis-Greenstein (cf. Whittet, 1992) mechanism, in which prolate grains are tumbling with their major axis perpendicular to the magnetic field lines. In turn this alignment means that the polarization vector is parallel to the direction of the magnetic field. Due to the wavelength dependence of the absorptivity of dust grains of different sizes (Greenberg, 1968) one may use multiband photopolarimetry to study the characteristic size of the dust grains responsible for the polarization (e.g. Il'in, Khudyakova & Reshetnikov, 1994). In this letter we report on such multiband photopolarimetry of stars behind the high galactic latitude cloud L1457.

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The molecular cloud L1457 (MBM 12) is the nearest known molecular cloud, at a distance of 65pc (Hobbs, Blitz and Magnani, 1986). It has been studied in many different tracers: CO (Magnani, Blitz & Mundy, 1985; Zimmermann & Ungerechts, 1990; Pound, Bania & Wilson, 1990), Cl (Ingalls, Bania & Jackson, 1994), Optical absorption (Hobbs, Blitz & Magnani, 1986; Hobbs et al., 1988), HI emission (Moriarty-Schieven, Andersson & Wannier, 1995) and HI absorption (Wannier, Andersson & Moriarty-Schieven, 1995). The L1457 cloud is located out of the galactic plane ($b=-34^\circ$) and is thought to reside within the local hot bubble (Hobbs, Blitz and Magnani, 1986). Based on a comparison of ^{13}CO line widths and mass estimates Pound, Bania and Wilson (1990) found that neither the cloud nor its constituent clumps are gravitationally bound. This conclusion is supported by the fact that no evidence for star formation in the cloud has been detected. There are two major reasons for studying the magnetic field in this cloud. First, the relative nearness of the cloud allows high resolution measurements of the structure in the magnetic field in a well-studied environment. Second, the cloud's location in the local bubble means that we might learn about the role and ordering of the magnetic field in the solar neighborhood.

2. Observations & Data Reduction

We used the photopolarimeter (Breger, 1979) on the 82" (2.1 m) telescope at McDonald Observatory during October 2-5, 1994 to perform multiband photopolarimetry in the extended Johnson system (UBVRI). The polarized standard HD 154445 was used to fix the instrument direction relative to the sky, assuming a P.A. of 90.10° for all bands except the U band for which we assumed $\theta_{\text{ref}}=87.9^\circ$ (Hsu & Breger, 1982). To determine the instrumental polarization we observed the unpolarized standard HD 154345 nightly. The instrumental polarization was constant, within the errors, during the run and so the

averaged values were used in the data reduction. A standard reduction procedure was employed in which the instrumental polarization was removed through corrections in the Stokes parameters, after which the coordinate system was rotated in accordance with the calibration observations. The uncertainty in the measured angle of the polarization was derived by either, standard propagation of errors for $\sigma_p/p \ll 1$ (e.g. Roe, 1992), yielding $\sigma_\theta = 28.65 \sigma_p/p$ (deg) or, by assuming a uniform probability distribution of the angle between 0 and 180 degrees for $\sigma_p \geq p$, yielding $\sigma_\theta = 51.96$ (deg).

3. Results & Discussion

The measured polarizations are presented in table 1. The first question to address is whether or not the measured polarization actually originates at the distance of L 1457. Of the 13 stars observed, 5 may be foreground objects, based on their apparent magnitudes and assuming all stars to be ordinary main sequence objects (we used the SIMBAD² data base for the stellar parameters. None of our stars have luminosity classification available). These stars are AG+19 215, AG+19 221, AG+19 222, AG+19 266 & AG+20 270. Three of the four stars showing no significant polarization are in this group, The remaining unpolarized object, AG+19 224 is at a large enough distance to be background to L 1457, but has the smallest apparent reddening (actually $E_{B-V} = -0.5$) consistent with no intervening dust. Two stars, AG+19 215 & AG+20 266, with small inferred distances nonetheless have measured polarization consistent with background objects, We assume this to be due to an error in our assumption about the luminosity classification, in that these stars may actually be luminosity class 111 objects. In such a case these stars are actually background objects as well. Hence for the 13 stars, 10 show direct agreement between whether they

²This research made use of the SIMBAD database, operated at CDS, Strasbourg, France.

arc background or not and whether they exhibit polarization or not and two of the remaining may be brought into agreement by assuming them to be giant stars. We thus conclude that the polarization measured towards L 1457 is indeed due to a magnetic field threading the cloud,

As can be seen from figure 1, the magnetic field in L1457, as delineated by the polarization, runs roughly parallel to the main axis of the CO and HI distribution (Zimmermann and Ungerechts, 1990; Moriarty-Schieven, Andersson & Wannier, 1995). The agreement between the direction of the polarization vectors and the large scale distribution is even better when the 100 μ m emission is used (cf. Hobbs, Blitz & Magnani, 1986, their figure 2). We note that the direction of the polarization in L 1457 is not directly connected to that in either of the two nearby major cloud complexes in Taurus or Perseus. Whereas the Taurus complex overall has a polarization direction roughly parallel to lines of constant galactic longitude (Goodman et al, 1990; their figure 3) and the direction of the polarization for the atomic halo of the Perseus complex runs parallel to the cloud complex or roughly "NE-SW" in galactic coordinates (Andersson and Wannier, 1995), the polarization in L1457 is roughly "NW-SE" in galactic coordinates.

For six of our stars the fluxes were great enough to warrant measurements in 4 or more filters. For these we fit the polarizations to the "Serkowski relation" (Serkowski, 1973; Whittet, 1992) allowing the factor "k" to vary

$$\frac{P_{\lambda}}{P_{\max}} = \exp \left\{ -k \cdot \ln^2 \left(\frac{\lambda_{\max}}{\lambda} \right) \right\} \quad (1)$$

to find the wavelength of maximum polarization. Three of these stars gave satisfactory fits. For the remaining ones the measurement uncertainties were too large to allow reliable fits or their intensities were too small to allow measurements in enough filters. The fits gave λ_{\max} for these three objects as follows: AG+1 8225: $0.54 \pm 0.01 \mu\text{m}$; AG+19 215: $0.56 \pm 0.01 \mu\text{m}$

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and AG+20 266; $0.54 \pm 0.01 \mu\text{m}$, which are typical values for interstellar polarization (Whittet, 1992). The value of the k parameter in equation 1 is higher, for the best fit solutions, than the typical interstellar value of 1.15 (Whittet, 1992) and hence the fitted p vs. λ curve is narrower. For our stars we get AG+1 8225: 7.3 ± 0.8 ; AG+19 215: 3.7 ± 0.6 and AG+20 266; 4.4 ± 0.6 (see fig. 2). If we assume that the polarization towards these three stars is caused by dust having a common set of parameters, we can average the polarization together to improve the significance of the fitted parameters. After scaling the polarizations to a common value of p_{max} of 0.5, the resulting fit gave $\lambda_{\text{max}} = 0.56 \pm 0.01$ and $k = 4.53 \pm 0.24$. Even though the significance of the functional form of the Serkowski relation is not clear in terms of physical parameters of the dust grains, the general shape of the polarization curve is reminiscent of the function obtained from Mie scattering theory (e.g. Rogers & Martin, 1979; Xing, 1993). Several different possibilities are available to explain the steeper spectral dependence of the polarization in 1,1457 compared to the typical interstellar value. Xing (1983) has shown that the width increases for progressively rounder spheroids as well as for lower values of the imaginary part of the refractive index. Another possibility is that the real part of the refractive index of the grains is significantly higher than that usual in the ISM (Wilking et al, 1980). This is intriguing in light of the fact that the wavelengths of maximum polarization for our stars are very close to the values typical in the ISM. To explore this possibility we used an extrapolation of the tabulated values of Rogers and Martin (1979) for the width of the theoretical polarization curve for an infinite cylinder (noting that since in their nomenclature $\rho = 4\pi a(m-1)/\lambda$, where a is the radius of the cylinder and m is the refractive index, then $\rho/\rho_{\text{max}} = \lambda_{\text{max}}/\lambda_{-1/2}$) to derive the halfpower width as a function of the refractive index. We then used the "Serkowski

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relation" to calculate the halfpower points of the observed polarization, as $\lambda_{\max}/\lambda_{\pm 1/2} = \exp\{\pm\sqrt{\ln(2)/k}\}$ Using these two relationships, and the somewhat *ad hoc* assumption that the two functions are close enough to each other to allow a direct comparison we can then estimate the refractive index corresponding to our measured value of k . In order to minimize the effect of the difference in functional form between theoretical and observational functions we then scaled the derived refractive index of our L1457 observations to that which this method derives for a k of 1.15. We find that the refractive index corresponding to $k=4.53$ is $m(4.53)=1.3*m(1.15)$. Since the refractive index of ice is generally smaller than that for refractory elements (e.g. graphite) by about a factor 2 (Greenberg, 1968), our result is consistent with the L1457 dust consisting of "naked" grains without icy mantles. Such a situation might result from L1457 residing in a hot bubble.

4. Conclusions

We have measured interstellar polarization towards 13 stars in the direction of the nearest known molecular cloud L1457. Based on spectroscopic parallaxes we conclude that the polarization seen is associated with the molecular cloud, implying an ordered magnetic field in the cloud. The wavelength dependence of the polarization shows a similar wavelength of maximum polarization to that typical for the ISM, but a significantly steeper drop-off on both sides of λ_{\max} , parametrized by $k=4.5$ in the Serkowski relation. We suggest that this may be due to the dust grains in L1457 lacking icy mantles.

ABL 1

star	RA(1950)	Dec(1950)	Sp.	V	(B-v)	d [†] [pc]	p [%]	angle [§] [°]
AG+1921 B V R I	2:49:37.05	19:14:08.80	K0	8.90	1.2	26/38	0.5550.06 0.73±0.04 0.66±0.03 0.47±0.04	-29±3 -32±2 -32±1 -25±3
AG+20 26 B v R	2:52:13.90	20:35:53.20	F2	8.80	0.4	140	0.15±0.04 0.11±0.04 0.14±0.03	-23±8 -35±52 10±6
AG+1822 U B V R I	2:52:59.79	18:57:05.70	F?	9.10	-0.1	≥87 [‡]	0.11±0.06 0.23±0.03 0.31±0.04 0.28±0.04 0.09±0.09	-48±52 -58±4 -63±4 -49±4 -81±52
AG+1921 B v R	2:54:13.60	19:53:51.20	G0	10.40	0.6	154	0.22±0.06 0.36±0.06 0.30±0.05	-16±8 -30±5 -10±5
AG+19 22 v R	2:54:42.89	19:49:03.50	G5	9.50	0.9	60	0.08±0.05	-29±52
AG+20 26 v R	2:54:47.84	20:38:45.30	F8	10.30	0.6	160	0.26±0.06 0.28±0.06	-26±7 -6±6
AG+20 26 U B v R I	2:55:15.21	20:23:27.90	G5	9.10	0.9	47/48	0.31±0.06 0.44±0.05 0.54±0.06 0.50±0.05 0.44±0.07	-19±6 -20±3 -25±3 -20±3 -9±5
AG+20 26 v R	2:55:27.35	20:27:40.10	G5	10.20	0.9	80	0.66±0.08 0.68±0.07	-19L3 -16±3
AG+19 22 v R	2:55:33.67	19:01:50.40	G0	8.30	0.6	57	0.06±0.05 0.11±0.04	-11±52 -7±52
AG+20 27 v R	2:55:41.72	21:02:22.00	K0	9.70	1.2	44	0.10±0.06 0.07±0.07	-15±52 -1±52
AG+1922 U B V R	2:56:19.56	19:47:29.20	F0	8.00	-0.2	120 [‡]	0.07±0.03 0.07±0.03 0.04±0.06 0.05±0.06	9±52 9±52 -51±52 -13±52
AG+1922 U B v R	2:56:36.26	19:52:06.30	A2	9.00	0.1	344	0.55±0.07 0.55±0.04 0.67±0.05 0.51±0.04	-20±4 -16±2 -19±2 -15±2
AG+1922 u B v R	2:58:32.96	19:59:07.30	F0	8.80	0.3	167	0.30±0.05 0.29±0.04 0.20±0.05 0.27±0.04	-7±5 -6±4 -14±6 -1254

[†]Spectroscopic parallax, assuming the stars to be on the main sequence.

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*For those stars which as main sequence would be foreground but in which we do detect polarization the distances given are for luminosity classes V/III.

‡For the two stars where (B-V) is negative we have assumed $A_V=0$ in the distance calculation.

§For $p > 3\sigma_p$, the uncertainty in the angle of the polarization is calculated using standard propagation of errors techniques (Roe, 1992); $\sigma_\theta = 28.65^\circ \sigma_p/p$. For $p < 3\sigma_p$ we assign uncertainties assuming a uniform probability distribution over the interval $[0, 180]$; $\sigma_\theta = 51.96^\circ$

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Figure Captions

Figure 1.

The polarization vectors towards L 1457 are plotted on an outline of the CO emission from the cloud adapted from Zimmermann & Ungerechts, 1990.

Figure 2.

Three stars in our sample yielded reliable fits to the Serkowski relation of the polarization as a function of wavelength. These fits, as well as that for the scaled average of the three stars, are shown with a curve (fat solid line) illustrating the shape of the "standard" Serkowski relation ($k=1.15$).

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Appendix A³.

Derivation of the measurement uncertainty in the angle of polarization:

If the measured polarization is much larger than the uncertainty in the polarization: $p \gg \sigma_p$ then we may use the standard formula for propagation of errors

$$\sigma_\theta^2 = \left(\frac{\partial\theta}{\partial Q}\right)^2 \cdot \sigma_Q^2 + \left(\frac{\partial\theta}{\partial U}\right)^2 \cdot \sigma_U^2 + \text{higher order terms}$$

Where Q & U are the Stokes parameters with uncertainties σ_Q & σ_U and

$$\theta = \frac{\arctan \frac{Q}{U}}{2}$$

Hence,

$$\frac{\partial\theta}{\partial Q} = \frac{1}{2} \frac{1}{1 - (Q/U)^2} \frac{1}{U} \quad \text{and} \quad \frac{\partial\theta}{\partial U} = -\frac{1}{2} \frac{1}{1 - (Q/U)^2} \frac{Q}{U^2}$$

Therefore:

$$\sigma_\theta^2 = \frac{1}{4} \frac{1}{(Q^2 + U^2)^2} \{U^2 \sigma_Q^2 + Q^2 \sigma_U^2\}$$

And since

$$\sigma_Q = \sigma_U = \sigma_p \quad \text{and} \quad p = \sqrt{Q^2 + U^2}$$

$$\sigma_\theta = \frac{1}{2} \frac{\sigma_p}{p} \text{ rad} \approx 28.65 \frac{\sigma_p}{p} \text{ deg}$$

For the situation where the Taylor expansion of the propagation of errors is not valid, i.e., $\sigma_p/p \geq 1$, the above expression does not hold. Maybe the most intuitive approach would have been to assume that Q and U are normally distributed and derive the distribution of $\arctan(Q/U)$ from this. However, the ratio of two normally distributed random variables is distributed according to the Cauchy distribution; $f_x(x) = \frac{1}{\pi} \frac{1}{1+x^2}$; $-\infty < x < \infty$, and since

this distribution does not have a well defined mean, we cannot derive an analytical expression for the variance of the polarization angle for large uncertainties in the Stokes parameters. However, we may find an upper limit to σ_θ by assuming that the parent population of the measured angle is uniformly distributed over the interval $[0, \pi]$. Then the expectation value is given by

$$\langle x \rangle = \int_a^b x f(x) dx = \int_a^b x \frac{1}{b-a} dx = \frac{b+a}{2}$$

The variance is given by:

³ This appendix will not appear in the published paper. We include it here since the explicit derivation of these relations are usually not presented.

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$$\sigma_x^2 = \langle x^2 \rangle - \langle x \rangle^2 = \frac{1}{3} \frac{b^3 - a^3}{b - a} - \left(\frac{b + a}{2} \right)^2 = \frac{(b - a)^2}{12}$$

and hence the uncertainty is given finally given by:

$$\sigma_x = \frac{b - a}{\sqrt{12}} = \frac{1}{\sqrt{12}} \frac{8.0}{\sqrt{12}} \approx 51.96 \text{ deg}$$



