HIGH-RESOLUTION MILLIMETER-WAVE MAPPING OF LINEARLY POLARIZED DUST EMISSION: MAGNETIC FIELD STRUCTURE IN ORION

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ABSTRACT

We present 1.3 and 3.3 mm polarization maps of Orion-KL obtained with the BIMA array at approximately 4" resolution. Thermal emission from magnetically aligned dust grains produces the polarization. Along the Orion “ridge” the polarization position angle varies smoothly from about 10° to 40°, in agreement with previous lower resolution maps. In a small region south of the Orion “hot core,” however, the position angle changes by 90°. This abrupt change in polarization direction is not necessarily the signpost of a twisted magnetic field. Rather, in this localized region, processes other than the usual Davis-Greenstein mechanism might align the dust grains with their long axes parallel with the field, orthogonal to their normal orientation.

Subject headings: instrumentation: polarimeters — ISM: magnetic fields — magnetic fields — polarization — stars: formation — techniques: interferometric

1. INTRODUCTION

Magnetic fields play many roles in the star formation activity in molecular clouds (see review by McKee et al. 1993). Polarization of radiation is one of the important signatures of interstellar magnetic fields (Hildebrand 1988). Spinning dust grains in the interstellar medium become partially aligned with the magnetic field, generally with their long axes perpendicular to the field (Davis & Greenstein 1951, hereafter DG). Thus, the thermal emission from grains at far infrared and millimeter wavelengths is partially linearly polarized, with polarization direction perpendicular to the magnetic field.

As the nearest region of OB star formation, the Orion molecular cloud has been studied intensively (see review by Genzel & Stutzki 1989). In the vicinity of the Kleinmann-Low Nebula (KL) the cloud contains at least two massive stars, IRc2 and the Becklin-Neugebauer object (BN), embedded within a flattened “ridge” of molecular gas that extends along a position angle of 30°. Polarization from aligned dust grains in Orion has been mapped at 100 μm with 35°–40° resolution (Novak et al. 1989; Gonatas et al. 1990; Schleuning 1998), at 350 and 450 μm with 18° resolution (Schleuning et al. 1997; Schleuning 1998), at 800 μm with 14° resolution (Aitken et al. 1997), and at 1.3 mm with 30° resolution (Leach et al. 1991). In all these maps the polarization vectors are roughly parallel with the molecular ridge, indicating that the large-scale magnetic field is perpendicular to the ridge. The uniformity of the polarization direction across the region suggests that the field is quite strong, of order 1 mG (Gonatas et al. 1990; Leach et al. 1991). The fractional polarization ranges from 4% to 8% except along the line of sight directly through KL, where it is significantly lower.

Higher angular resolution is needed to probe the polarization pattern near KL. Heretofore, this has been possible only at near- and mid-IR wavelengths, where the competing effects of absorption, emission, and scattering all influence the polarization direction. Some of the more secure results are obtained by mapping the polarization of the 2 μm S(1) line of H₂ (Hough et al. 1986; Burton et al. 1991; Chrysostomou et al. 1994). The line emission (assumed unpolarized) originates from shock-excited H₂ in the bipolar outflow from IRc2. Absorption by aligned grains in front of the outflow produces the polarization. Aitken et al. (1997) also mapped the continuum polarization at 12.5 and 17 μm; spectropolarimetry suggests that it, too, is mostly attributable to absorption. These studies all find that the polarization vectors are twisted near KL. The authors argue that this is evidence for a toroidal magnetic field in a disklike structure centered on IRc2.

In this Letter we present the first interferometric polarization maps of Orion at millimeter wavelengths, in which the polarization arises unambiguously from emitting grains. These high-resolution maps confirm the abrupt change in polarization direction near IRc2 first detected in the 2 μm data. We argue that in this small region the bipolar outflow from IRc2 might align the grains with their long axes parallel with the magnetic field, orthogonal to their usual orientation. Thus, it is not certain that the change in the polarization direction arises from a twisted magnetic field.

2. OBSERVATIONS AND DATA ANALYSIS

Observations were made with the 10 antenna BIMA array (Welch et al. 1996) in 1997 March, November, and December and 1998 January. Data were obtained at 90 GHz (λ = 3.3 mm) with the antennas in the B and C configurations, and at 230 GHz (λ = 1.3 mm) with only the C configuration.

Linear polarization measurements with interferometers are best done with circularly polarized feeds (see Thompson, Moran, & Swenson 1986). This minimizes the effect of gain errors, as the cross-correlation of opposite circular polarizations does not involve the Stokes total intensity (I) parameter. Quarter wave plates are used in front of the linearly polarized BIMA feeds to obtain left (L) or right (R) circular polarizations. Since only a single polarization is received, L and R are time-multiplexed on each antenna using a fast Walsh function switching pattern in order to sample all possible cross correlations (LL, LR, RL, RR) on every baseline. The data were averaged over

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Fig. 1.—Polarization map of Orion-KL at 3.3 mm. Contours indicate the total 3.3 mm flux density (Stokes I) and are drawn at 12, 25, 50, 60, 72, 84, 95 percent of the peak value of 360 mJy beam$^{-1}$. The noise level was $\sim 15$ mJy beam$^{-1}$. Vectors show the percentage polarization and position angle wherever linearly polarized flux was detected with $3 \sigma$ or greater significance. Offsets are relative to IRc2-source I at $\alpha = 5^h35^m14^s50.5, \delta = -5^\circ22'30''45''$ (J2000). The position of IRc2 is indicated by a hollow square, BN by a cross. The $6'' \times 2''$ synthesized beam is shown by the ellipse at lower left.

Stokes parameters. These maps were deconvolved independently and then combined to produce maps of the linear polarization intensity, the fractional polarization and the position angle. The synthesized beam size was $6'' \times 2''$ at 3.3 mm and $4'' \times 2''$ at 1.3 mm.

3. RESULTS

Figures 1 and 2 display the 3.3 and 1.3 mm polarization maps. Almost all of the emission at these wavelengths is thermal radiation from dust. We have not corrected the maps for contamination by free-free emission from the compact circumstellar envelopes associated with BN and IRc2 ($30$ to $150$ mJy; Plambeck et al. 1995), nor from the extended foreground H$\ii$ region (important only along the eastern edge of the 3.3 mm map, judging from Figures 1 and 2 of Wright et al. 1992).

Polarization vectors are plotted only where the linearly polarized intensity ($Q^2 + U^2$)$^{1/2}$ is greater than $3 \sigma$, where $\sigma$ (the rms noise level in the $Q$ and $U$ maps) is 1.8 mJy beam$^{-1}$ at 3.3 mm and 12 mJy beam$^{-1}$ at 1.3 mm. This cutoff corresponds to an uncertainty of approximately 10$''$ in the polarization position angle P.A. = $1/2 \tan^{-1} (U/Q)$. The percentage polarizations we observe are as high as 20% in some directions, particularly near the edges of the emission region. Such high values probably are not significant. They can occur if the Stokes $I$ emission region is more extended than the linearly polarized region. In that case, the interferometer resolves out some of the extended emission in the $I$ image but detects most of the linearly polarized flux, so one overestimates the fractional po-

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See also http://www.atnf.csiro.au/computing/software/miriad.
Table 1 lists the polarizations and formal errors for four independent positions (separated by at least one synthesized beamwidth) where we have both 3.3 and 1.3 mm data. The 1.3 mm maps were convolved to the same resolution as the 3.3 mm maps for this comparison. The 1.3 and 3.3 mm polarization position angles differ by at most 15°, which is within the expected uncertainties. The rotation angle due to Faraday rotation is given by $\Omega = \lambda^2 R_M$, where $\lambda$ is the wavelength and $R_M$ is the rotation measure. From measurements at two different frequencies, one can compute the rotation measure as $R_M = \Delta\Omega/(\lambda_2^2 - \lambda_1^2)$. Our data imply $\Delta\Omega < 0.25$ radians, so $R_M < 2.8 \times 10^4 \text{ rad m}^{-2}$. Using this upper limit for the rotation measure, we find $|n_B dl| < 0.035 \text{ G cm}^{-1}$. Thus, if the foreground H ii region has an electron density of $10^4 \text{ cm}^{-3}$ over a distance of 1 pc (Wilson & Jäger 1987), the average line-of-sight magnetic field through the H ii region is $\leq 35 \mu\text{G}$.

4. DISCUSSION

The most striking feature in our maps is the abrupt change in polarization direction $\sim 5^\circ$ south of IRC2. The polarization position angle rotates from 0° to 90° as one moves eastward from the Orion ridge through this “anomalous” region, on both the 1.3 and 3.3 mm maps. The twisted polarizations south of IRC2 were not detected in previous millimeter, submillimeter, and FIR polarization maps because of inadequate angular resolution. When convolved to $20^\prime$ resolution, our 3.3 mm polarization map closely resembles the earlier maps (cf. Leach et al. 1991; Schleuning 1998). In particular, it shows the polarization “hole” toward KL that results from averaging across the region where the polarization direction varies.

Our data are consistent with the 2 $\mu$m polarization maps of the S(1) line of H$_2$ (Hough et al. 1986; Burton et al. 1991; Chrysostomou et al. 1994). At 2 $\mu$m the polarization is produced by dust absorption, rather than emission, so the polarization vectors should be orthogonal to the ones we measure. If we overlay our data on the 2 $\mu$m map shown in Figure 1 of Chrysostomou et al. (1994), the polarization vectors are orthogonal almost everywhere, including the anomalous region. Comparing our data with the 12.5 and 17 $\mu$m polarization maps of Aitken et al. (1997) is more difficult because the mid-IR brightnesses are low southeast of IRC2. These maps do show, however, that southwest of IRC2 the polarization direction is roughly orthogonal to that along the Orion ridge, similar to our results.

The anomalous polarization region lies along the southern edge of the Orion “hot core” dust continuum peak. Molecular line observations (Blake et al. 1987; Genzel & Stutzki 1989; Wright, Plambeck, & Wilner 1996) indicate that gas kinetic temperatures in the hot core range from 150 to 300 K, with densities $n(\text{H}_2) \sim 10^7 \text{ cm}^{-3}$. The Orion “compact ridge” feature overlaps the hot core along this same line of sight; it is a bit cooler (80–140 K) and less dense ($10^6 \text{ cm}^{-3}$). It is likely that the hot core is physically near IRC2, probably within 1000 AU. The compact ridge also seems to be closely linked to the hot core and IRC2. By contrast, the ridge emission west of the hot core, where the polarization position angles are “normal,” probably arises in gas farther from IRC2.

Many possible mechanisms can align dust grains in a molecular cloud, and hence produce linear polarization (Lazarian, Goodman, & Myers 1997, Table 1). Before discussing these processes, it is worthwhile to emphasize that, regardless of the alignment mechanism, the polarization direction must always be correlated with the magnetic field direction in the cloud (Martin 1971; Roberge 1996). This is because a spinning grain acquires a magnetic moment, primarily through the Barnett effect, and the interaction of this moment with the magnetic field causes the grain to precess around the field direction. For a 2000 Å diameter grain in a 1 mG field, this Larmor precession period is only a few hours (Roberge 1996), orders of magnitude shorter than the time required for any alignment mechanism to change the grain’s angular momentum. Thus, the net polarization from an ensemble of grains, all precessing around the field, must be symmetrical with respect to the magnetic field, either parallel or perpendicular to it.

In most regions of the interstellar medium grains are assumed to be aligned via paramagnetic relaxation (the DG mechanism), which damps the components of a grain’s angular momentum perpendicular to $B$, gradually aligning the spin axis with the magnetic field direction. Internal damping due to Barnett relaxation normally causes the grain to spin about its axis of greatest moment of inertia (Purcell 1979), so the long axis of the grain is oriented perpendicular to the field. Presumably, this is the situation along most of the Orion ridge. If the grains in the anomalous region also are aligned via the DG mechanism, then either the magnetic field in this region must be twisted or these grains are rotating about their axes of least moment of inertia. The latter occurs where the dust grains are hotter than the gas (Jones & Spitzer 1967). There is little indication that this is the case in Orion: the 20–30 $\mu$m dust color temperature across the entire KL region is roughly 100 K (Wynn-Williams et al. 1984), less than or comparable to the gas kinetic temperatures inferred for the hot core and compact ridge. One may also dismiss this possibility because it leads to extremely low alignment efficiencies (Lazarian, Goodman & Myers 1997, Fig. 2). We conclude that, if DG alignment applies, the magnetic field in the anomalous region must be almost orthogonal to that in the ridge.

Chrysostomou et al. (1994) and Aitken et al. (1997) have modeled this as the result of a toroidal magnetic field in a dense circumstellar disk associated with IRC2. We are suspicious of this hypothesis for several reasons. First, the anomalous polarization region is not centered on IRC2. Second, in our maps the polarization direction does not seem to twist smoothly, but
instead jumps abruptly by 90°, at the edge of the anomalous region. Finally, in a region as dense as the hot core it is difficult for DG alignment to overcome the randomizing effect of gas-grain collisions. The success of the DG mechanism would require suprathermal rotation (Purcell 1979) and/or superparamagnetic damping (Jones & Spitzer 1967).

Although DG alignment in the hot core cannot be ruled out, we are motivated to consider alternative alignment mechanisms that might produce the observed change in polarization direction without invoking a twisted magnetic field. One such mechanism is alignment by the intrinsic angular momentum of photons (Harwit 1970). In an anisotropic radiation field, absorbed photons preferentially excite the component of a grain’s angular momentum parallel to the photon flux. Purcell & Spitzer (1971) showed that cold grains cannot be aligned by an anisotropic flux of optical photons because roughly 300 infrared photons, each with intrinsic angular momentum $\hbar$, are emitted in random directions for each optical photon absorbed. Aitken et al. (1985) pointed out, however, that the mechanism could be important for small grains close to a cool source of high luminosity (such as IRc2), where infrared, not optical, photons cause the alignment. However, the calculations given in § 4.1 of Aitken et al. (1985) show that in a region as dense as the Orion hot core gas-grain collisions impart 10 times the mean squared angular momentum of infrared photons (using $n \sim 10^6$ cm$^{-3}$, $a \sim 10^{-5}$ cm, $T_{\text{gas}} \sim 150$ K), so the alignment efficiency is very low.

A more promising mechanism is Gold (1952) alignment, in which gas streaming past the grains excites their angular momenta perpendicular to the flow direction, causing the grains to rotate with their long axes parallel to the flow. Efficient alignment takes place if the speed is greater than the random thermal velocities of the gas particles. IRc2 is known to be the source of a supersonic bipolar outflow that certainly is adequate to align grains. The outflow is well traced by the CO millimeter transitions and is roughly perpendicular to the ridge, at an angle of 15° to the large-scale magnetic field direction. Lazarian (1994, 1997) modified the Gold alignment theory to take into account the effects of suprathermal rotation, Larmor precession, and internal alignment via Barnett relaxation. His theory predicts that oblate grains will be aligned with their long axes parallel with the magnetic field if the angle between the outflow and the field is less than $\cos^{-1}(1/\sqrt{3})$ ($\theta \sim 55°$). The alignment efficiency decreases as the angle between the outflow and the magnetic field increases until this critical angle is reached. If Gold alignment is responsible for the anomalous polarizations south of the hot core, then the magnetic field throughout the entire Orion-KL region could be relatively straight.

5. Conclusions

We have made the first interferometric observations of the polarization from dust emission in the Orion BN/KL region, at wavelengths of both 1.3 and 3.3 mm. We find that the decrease in fractional polarization toward KL previously seen with single-dish observations is a result of polarization structure that is averaged out by larger beams. In particular, our maps show that the polarization direction changes abruptly by 90° in a small region south of the Orion hot core. If the grains are aligned everywhere by the Davis-Greenstein mechanism, then the magnetic field in this anomalous region is almost orthogonal to the large-scale field in the Orion ridge. However, it is plausible that the grains in this region are aligned by a wind from IRc2, and that the magnetic field is relatively straight. These results suggest that one should be cautious in using polarization data to infer the magnetic field structure around young stars, because of the possibility that the grains are mechanically aligned by outflows.

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