POLARIZED CO EMISSION FROM MOLECULAR CLOUDS

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ABSTRACT

Linearily polarized, nonmasing, rotational lines have been detected for the first time in the interstellar medium. This effect occurs in molecular clouds with a magnetic field and traces the field direction, offering an alternative technique to dust emission polarimetry. The line polarization mechanism is similar to that in masers, but with lower degrees of polarization (~1%). We have detected the effect toward the Galactic center and its surrounding “2 pc ring” and in the molecular clouds S140 and DR 21 (tentatively), in the lines CO $J = 2\rightarrow1$ and $J = 3\rightarrow2$ and $^{13}$CO $J = 2\rightarrow1$. The deduced magnetic field directions agree well with previous dust polarimetry results, confirming that the line polarization is a real effect. This new technique will be useful in sources that are too faint for dust polarimetry and can also be used to investigate the three-dimensional morphology of magnetic fields in cases in which the velocity structure of the clouds is known.

Subject headings: ISM: magnetic fields — polarization

1. INTRODUCTION

Magnetic fields are thought to play an important role in the evolution of the interstellar medium. However, in dense molecular clouds in which stars form, these fields are very difficult to observe. The normal technique is to measure the linearly polarized emission from dust grains, since the grains are partially magnetically aligned and have their maximum emission along the long axes, perpendicular to the field. This technique has been used successfully at millimeter to far-infrared wavelengths (see Hildebrand 1996 for a review).

Alternatively, it has been predicted that the emission from rotating molecules can be polarized (Goldreich & Kylafis 1981), and this effect could also be used to trace magnetic fields. Rotating molecules have a magnetic moment which interacts with the field, splitting the rotational quantum levels ($J$) into magnetic sublevels ($M$). Only transitions in which $M$ changes can contribute to emission that is polarized perpendicular to the field. Then, if the cloud is anisotropic, population imbalances of the $M$ levels arise, and radiation escape probabilities vary with direction (Goldreich & Kylafis 1981). Photons with some particular polarization can escape more readily than others, resulting in different line intensities for the directions perpendicular and parallel to the field, and this produces linearly polarization spectra. Typical polarization levels are predicted to be ~1% (Deguchi & Watson 1984).

In principle, this effect is an ideal magnetic field tracer, since molecular lines such as those of CO are bright in many clouds, and a 1% modulation should be detectable. However, previous experiments have been unsuccessful (Wannier, Scoville, & Barvainis 1983; Barvainis & Wootten 1987; Lis et al. 1988; Glenn, Walker, & Jewell 1997). The early experiments suffered from instrumental problems, and some nominal detections were thus thought to be untrustworthy (Wannier et al. 1983). More recently, improved receiver performance has led to much lower polarization limits, such as $p$(HCO$^+$ $J = 1\rightarrow0$) < 0.3% in DR 21 (Glenn et al. 1997), which is below predicted levels (Lis et al. 1988). This suggests either that the theory is in error or that special conditions are required for substantial line polarization to occur in clouds. The latter hypothesis is supported by the theoretical work of Deguchi & Watson (1984), who found that $p$ is maximized for line optical depth $\tau \sim 1$ and collisional and radiative transitional rates that are roughly equal. We have therefore searched for polarization in CO lines in moderately dense molecular environments, where these conditions may be met. In this Letter, we present the first line polarization detections, in a range of molecular clouds and three independent spectral lines. These results are complementary to very recent detections of line polarization in the circumstellar envelope of the asymptotic giant branch star IRC +10216 (Glenn et al. 1997) and in compact cores surrounding OMC-1/IRC2 (BIMA 1.3 mm interferometry; D. Crutcher and R. Rao 1998, private communication).

2. OBSERVATIONS

The observations were made in the period 1995 July to 1997 July at the James Clerk Maxwell Telescope (JCMT) located on Mauna Kea, Hawaii. A rotating quartz half-wave plate (Murray et al. 1992) was mounted in front of the single-polarization facility heterodyne receiver RxA2 (Davies et al. 1992). The data were taken by stepping the wave plate at 22.5 intervals around 360°, thus rotating the source plane of polarization with respect to that accepted by the receiver and recording a spectrum at each position. Sky emission was subtracted by switching to an off-source position up to a degree away, and the integrated intensities of the lines were then fitted for the polarization modulation using a least-squares procedure (Nartallo 1995). Instrumental polarization (IP) was subtracted, and the residual signal was corrected for source parallactic angle and a rotation corresponding to the receiver position. (The absolute angle of the wave plate’s fast axis had been established previously with a polarizing grid). The final percentage polarization and error in the position angle were corrected for bias effects (due to the vector nature of $p$), as described by Wardle & Kronberg (1974). Polarized spectra were also constructed using a direct subtraction method (e.g., Wannier et al. 1983) and IP and rotation corrections as above.
Integration times used were generally 16 s per wave-plate position, sufficiently short that sky variations had only a small effect on the signal. Some automatic despiking was used in the analysis, removing typically 1–2 of the 16 fitted points in order to improve the results in a $\chi^2$ test. For one source (southwest in CO $J = 2–1$, see below), an empirical criterion was also used to completely reject some cycles in which about half of the noise estimates per cycle showed anomalously high values, indicating serious sky instability. Between five and 17 complete wave-plate cycles per source were made to detect the polarization, with signal-to-noise ratios of typically 3.5 (greater than 99% confidence levels). This is sufficient to determine the position angle error $\Delta\theta$ to ±8° (e.g., Wardle & Kronberg 1974).

An important aspect of the observations is the removal of instrumental polarization. An incoming unpolarized signal will become polarized due to effects of the telescope optics and transmission through the woven JCMT windblind, which has a spacing comparable to millimeter wavelengths. We measured this IP using Mars, Saturn, and Jupiter, since the planets have very low intrinsic degrees of polarization (Clemens et al. 1990). The IP levels were 0.8%–1.1%, with measured errors of 0.15%–0.3%. For the reduction in this Letter, we have mainly used Saturn, which had an apparent diameter of 17″–19″ during our observations and was thus well matched to the JCMT beam (21″ FWHM at the CO $J = 2–1$ frequency of 230 GHz). During the CO $J = 3–2$ observations at 345 GHz, Saturn was not available, and Jupiter was used instead (45″ diameter). The IPs were found to depend only slightly on frequency within the passband ($\delta IP = \pm 0.0%$–0.3%) and varied little with source elevation ($\delta IP \sim \pm 0.15\%$). The IPs subtracted were for the main beam only, but sidelobe instrumental polarization was found to be negligible. Measurements using Jupiter at 230 GHz showed that the effective off-axis IP contributed a residual of around 0.1%, with the planet offset just outside the main beam, and covering a region 45″ in diameter in sidelobes of ~1% amplitude relative to the main beam.

We also investigated various instrumental effects that can mimic a polarization signal, including calibration changes, reflection modulations, and beam-shape distortions. Calibration was done using hot, cold, and sky loads at the start of each wave-plate cycle, and an additional calibration, using the off-position as the sky signal, was done for each individual spectrum. The intensity calibration is therefore very accurate. Wave-plate reflections, which can modulate the signal as the plate rotates, were minimized by mounting the polarimeter module at a slight angle to the incoming beam. Finally, an elliptical beam could cause signal modulations, since the wave-plate movement effectively rotates the beam over the source. Bright regions at the edges of the beam could then be included in the signal for some wave-plate angles. However, we have estimated this effect, using as an example a map around our southwest Galactic center point (see below), and for a 5% beam ellipticity, the effective “polarization” introduced is less than 0.05%.

Instrumental polarization can thus be subtracted quite reliably, to a limit of about $\Delta IP \sim 0.3\%$. This uncertainty arises mainly from the choice of planet to use for the IP, since it is difficult to match the planet and source sizes exactly. Our line polarimetry technique will therefore only give reliable position angles, and hence field directions, when the source polarization is significantly larger than ~0.3%.

### 3. RESULTS

The predicted polarization level is maximized if the source has well-ordered magnetic and velocity fields (Goldreich & Kylafis 1981; Lis et al. 1988), so we searched for sources that met these criteria. An ideal target is the “2 pc ring” around the Galactic center, which has a roughly linear magnetic field and constant rotational velocity (Hildebrand et al. 1993; Sutton et al. 1990). Two positions were observed in this ring, and the results for CO $J = 2–1$ polarization are presented in Table 1. Consistent results were obtained on two separate runs, with $\delta \theta$ differing at only about the 1.5 σ level. The observations were made at different parallactic angles for the two runs, so the agreement after de-rotation indicates that we are not just measuring an instrumental effect.

To confirm these detections, we reobserved one of these positions in CO $J = 3–2$, obtaining a similar position angle. We also looked for polarization in $^{13}$CO $J = 2–1$ toward Sgr A* and observed two molecular clouds to determine if line polarization is also present in star formation regions. S140 was detected in $^{13}$CO $J = 2–1$ polarization, and DR 21 was detected in CO $J = 2–1$ (tentatively). These results are listed in Table 1.
A good test of the reality of the line polarization is the position angle measured. This can be either parallel or perpendicular to the magnetic field (Kylafis 1983) and should thus be at $0^\circ$ or $90^\circ$ to the direction of dust polarization (which is always perpendicular to the field). For the Sgr A* and 2 pc ring positions, 100 $\mu$m dust polarization has been detected by Hildebrand et al. (1993), and there is good agreement with the CO and $^{13}$CO results. The difference in position angle is $2^\circ \pm 8^\circ$ for the northeast ring position in the CO $J = 2\rightarrow 1$ line and $81^\circ \pm 9^\circ$ for the southwest position in the CO $J = 2\rightarrow 1$ and $J = 3\rightarrow 2$ lines combined. (The CO $J = 3\rightarrow 2$ result alone has a larger angle deviation, but this could be explained by small-scale field structure, since the beam size is $\approx$2.5 times smaller than that for the 100 $\mu$m data.) The line polarization is found to be perpendicular to the field at the northeast point and parallel toward southwest, a difference that is probably related to viewing angle effects (Kylafis 1983), since the points lie at different ring radii.

For Sgr A*, the projected ring velocity is $\approx$0 km s$^{-1}$, similar to foreground gas, so the $^{13}$CO polarization was found for the complete spectrum. The difference in angle with the dust data is $4^\circ \pm 9^\circ$, implying that both of these optically thin tracers are detecting the same net magnetic field for the clouds along the line of sight.

The two molecular cloud sources observed were DR 21 and S140 IRS 1, which have previously been observed in 800 $\mu$m dust polarimetry at the JCMT (Minchin & Murray 1994; Minchin, Bonifácio, & Murray 1999). For DR 21, the CO optical depth is very high ($\tau \sim 7$ from comparison with a $^{13}$CO spectrum and assuming $^{12}$C/$^{13}$C = 53; Langer & Penzias 1990). It is therefore not surprising that the measured $p$ is small and only marginally detected, since both polarizations tend to saturate (Goldreich & Kylafis 1981). Also, since only the front parts of the cloud will be detected in CO, the estimated position angle is not the same as in the dust data (Table 1). In contrast, for the more optically thin $^{13}$CO emission in S140 IRS 1, there is very good agreement in position angles ($\delta\theta = 6^\circ \pm 10^\circ$).

4. DISCUSSION

Polarization has been detected at five points in star formation regions and around the Galactic center in a total of three spectral lines. The degree of polarization ranges from 0.5% to 2.4% and is at about the level predicted theoretically. For example, Deguchi & Watson (1984) modeled the polarization of the $J = 2\rightarrow 1$ transition of CO, assuming simple linear magnetic fields and velocity gradients, and found $p$ up to 0.5%--4.5% for gas densities of $\sim$10$^4$ cm$^{-3}$. Also, the position angles found from the line observations are in excellent agreement with those derived previously from dust polarimetry. The combination of these factors indicates that real detections of line polarization have been made.

The results have shown that polarized CO and $^{13}$CO lines are good tracers of magnetic fields, under suitable conditions. These are chiefly that the optical depth should be $\sim$1 and that the collisional and radiative rates for the transition should be comparable (Goldreich & Kylafis 1981). For the CO $J = 2\rightarrow 1$ line, the latter condition corresponds to gas densities of $\sim$10$^4$ cm$^{-3}$ at temperatures of 30 K, which are realistic parameters for core regions of giant molecular clouds. In the particular case of the Galactic center ring, the estimated $n_{\text{H}_2}$ is $2 \times 10^4$ cm$^{-3}$ (Sutton et al. 1990; Zylka, Mezger, & Wink 1990), and the ring optical depth is estimated at 1.3--1.6 (using the $^{13}$CO/CO line ratio and an isotopic ratio of 25; Wilson & Matteucci 1992; Langer & Penzias 1990). Under these conditions, $p$(CO $J = 2\rightarrow 1$) should be $\leq 1.5\%$ (Deguchi & Watson 1984), and our measured $p$(CO)'s are $\approx 0.5\%$--1.7%, in good agreement. In some circumstances, other effects could contribute to the polarization, such as selective excitation of the sublevels by IR pumping (Morris, Lucas, & Omont 1985), but this will not be significant for general cloud material, and even for the strongly centrally illuminated Galactic center region, we do not see the predicted radial or tangential polarization directions in the CO data (Table 1).

The polarization level falls below detectable limits ($p$ comparable to 0.3%) for high $\tau$, as for example in DR 21 (Table 1). We have also searched for CO $J = 3\rightarrow 2$ polarization in more optically thick regions of the Galactic center ring and found $p$ to be typically only $\sim$0.4%. Thus, previous nondetections of line polarization may have been partly due to high optical depths in the molecular cores observed. Density is also critical, since at high $n_{\text{H}_2}$, collisions scramble the sublevel level populations, and this can explain, for example, low polarization in the very dense NH$_2$ core in GMC-1 (53; Barvainis & Wooten 1987). More recently, Glenn et al. (1997) have measured a low polarization in the DR 21 core in the HCO$^+$ $J = 1\rightarrow 0$ line. They found $p \sim 0.24\% \pm 0.04\%$ (below the level of possible instrumental effects), and this low level may be due to the high core optical depths and/or densities. The CO lines of moderate optical depth therefore appear to be the most suitable for spectropolarimetry, since they trace moderate density material in more extended regions of molecular clouds.

A particular advantage of line polarimetry is that the magnetic field components of different clouds along the line of sight can be separated. This is illustrated in Figure 1, which shows the polarized CO $J = 2\rightarrow 1$ spectra toward the northeast and southwest ring positions. The bottom two spectra are the Stokes parameters $Q(v)$ and $U(v)$ (see, e.g., Wannier et al. 1983), representing orthogonal components of the polarization, and the top plot shows the total intensity spectrum $I(v)$ (on a 1% scale). The percentage polarization is found from $p = I^{-1} |(Q^2 + U^2)|^{1/2}$, and the position angle is given by $\theta = 1/2$ tan$^{-1}(U/Q)$. It can be seen that other sources, such as the well-known “+20 km s$^{-1}$” and “+50 km s$^{-1}$” clouds (e.g., Zylka et al. 1990) are also polarized, but have $Q$ and $U$ components of different magnitude and sign to the ring, implying different field directions. (Note that the exact polarization parameters for these clouds are uncertain, since they are spatially extended, so the subtraction of the Saturn IP may not be appropriate.)

Figure 1 illustrates that net polarization for the whole spectrum will not represent any of the individual magnetic fields. This is a problem for dust polarimetry, where the clouds cannot be separated (although in the case of the 2 pc ring, there is little dust emission from foreground clouds; Hildebrand et al. 1993). The particular advantage of line polarimetry is that field directions for clouds at different velocities can be determined separately. Thus, this new polarimetry technique provides substantial information on the three-dimensional field structure in sources with velocity discrimination (such as rotation, infall, or outflow), even though the line-of-sight field components cannot be detected.

5. CONCLUSIONS

Polarized rotational lines have been detected for the first time in molecular cloud sources. The polarization levels are $\approx 0.5\%$--2%, and the deduced magnetic field directions agree
Fig. 1.—Polarization spectra toward the northeast (left) and southwest (right) ring positions. The top spectrum is total intensity $I$ on a $T_A$ antenna temperature scale, divided by 100. The middle and bottom spectra are the Stokes parameters $Q$ and $U$ (see text), and the vertical bars represent typical standard errors in each detected channel. The ring velocities (Serabyn et al. 1986) are marked by the dashed vertical lines.

very well with previous dust polarimetry data. The advantages of line polarimetry are that field orientation can be found as a function of velocity and also that faint sources, which may not have significant dust emission, can be observed. A 90° directional ambiguity can be a problem for some sources, although this may be resolved with sufficient source information (Kylafis 1983). CO emission is often bright, even where the dust (sub)millimeter continuum is not detectable, such as in low column density sources. This new technique thus has potential for mapping the three-dimensional magnetic structure of sources such as star formation regions, protostellar core/outflow systems, and circumstellar envelopes, as well as for understanding the Galactic center field morphology.

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