FIRST OBSERVATIONS OF THE MAGNETIC FIELD GEOMETRY IN PRESTELLAR CORES

D. Ward-Thompson and J. M. Kirk
Department of Physics and Astronomy, University of Cardiff, P.O. Box 913, Cardiff, CF2 3YB, Wales, UK

R. M. Crutcher
Department of Astronomy, University of Illinois at Champaign-Urbana, 102 West Green Street, Urbana, IL 61801; crutcher@astro.uiuc.edu

J. S. Greaves and W. S. Holland
Joint Astronomy Centre, 660 North Aohoku Place, University Park, Hilo, HI 96720

AND

P. André
CEA, DSM, DAPNIA, Service d’Astrophysique, C.E. Saclay, F-91191 Gif-sur-Yvette Cedex, France

Received 2000 March 9; accepted 2000 June 1; published 2000 July 7

ABSTRACT

We present the first published maps of magnetic fields in prestellar cores to test theoretical ideas about the way in which the magnetic field geometry affects the star formation process. The observations are JCMT-SCUBA maps of $\lambda 850 \mu m$ thermal emission from dust. Linear polarizations at typically 10 or more independent positions in each of three objects, L1544, L183, and L43, were measured, and the geometries of the magnetic fields in the plane of the sky were mapped from the polarization directions. The observed polarizations in all three objects appear smooth and fairly uniform. In L1544 and L183 the mean magnetic fields are at an angle of $\sim 30^\circ$ to the minor axes of the cores. The L43 B-field appears to have been influenced in its southern half such that it is parallel to the wall of a cavity produced by a CO outflow from a nearby T Tauri star, while in the northern half the field appears less disturbed and has an angle $44^\circ$ to the core minor axis. We briefly compare our results with published models of magnetized cloud cores and conclude that no current model can explain these observations simultaneously with previous ISOCAM data.

Subject headings: ISM: clouds — ISM: individual (L43, L183, L1544) — ISM: magnetic fields — stars: formation

1. INTRODUCTION

It has become increasingly clear that magnetic fields play an important role in the formation and evolution of molecular clouds and in the process of star formation. Observations of the geometry of magnetic fields in molecular clouds therefore appear to be essential to a full understanding of the star formation process. Submillimeter polarimetry is one of the most direct methods of studying magnetic field geometries in star formation regions (e.g., Goodman 1996). Such observations should also allow one to assess the relative importance of the uniform and tangled fields. A high level of polarization, uniform in direction, indicates a well-ordered field that is not significantly tangled on scales smaller than the beam. Furthermore, the fact that the submillimeter polarimetry only traces the densest material means that observations do not sample long path lengths of magnetic field between observer and object. One should therefore be able to test the geometrical predictions of theoretical models.

Virtually all observations of magnetic fields in dense molecular clouds to date have been toward regions of active star formation, including high-mass star formation sites with H II regions. Although column densities and temperatures of dust grains are higher in such regions, making mapping of the magnetic fields more feasible, there is the danger that star formation activity may have changed the initial geometry of the magnetic fields. It is therefore highly desirable to map magnetic field geometries in objects that are believed to be gravitationally bound but have not yet formed a central hydrostatic protostar.

P. C. Myers and coworkers (see Benson & Myers 1989 and references therein) identified a large number of ammonia cores, which were shown to be sites of low-mass star formation. Beichman et al. (1986) separated the ammonia cores into those in which star formation had already commenced (those with IRAS sources) and the “starless” cores (those without IRAS sources). Ward-Thompson et al. (1994) observed the submillimeter continuum emission from starless cores to ascertain their morphologies and densities and named the most centrally condensed objects “pre-protostellar” (or “prestellar” for brevity) cores. André, Ward-Thompson, & Motte (1996) carried out a detailed study of the prestellar core L1689B to compare it with the predictions of an ambipolar diffusion model and found some discrepancy with the magnetic field strength required by the model. Ward-Thompson, Motte, & André (1999) observed the millimeter continuum emission from a larger number of prestellar cores to ascertain their detailed radial density profiles and confirmed the central flattening that had previously been observed by Ward-Thompson et al. (1994). A small number of cores are sufficiently bright at $\lambda 850 \mu m$ for polarization mapping observations to be currently possible. In this Letter we present the first published submillimeter continuum polarization observations of prestellar cores, which were carried out to test the predictions of theoretical models.

2. OBSERVATIONS

Submillimeter continuum polarimetry observations at 850 $\mu m$ were carried out using the Submillimeter Common-User Bolometer Array (SCUBA) camera on the James Clerk Maxwell Telescope (JCMT) on Mauna Kea, Hawaii, on the mornings of 1999 March 15 (L183 and L43) and September 15

1 JCMT is operated by the Joint Astronomy Centre, Hawaii, on behalf of the UK PPARC, the Netherlands NWO, and the Canadian NRC. SCUBA was built at the Royal Observatory, Edinburgh. SCUBAPOL was built at Queen Mary and Westfield College, London.
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Fig. 1.—Dust continuum emission at $\lambda$850 $\mu$m from the L1544 prestellar core. The Stokes $I$ map is shown as a gray scale with contours overlaid. Contour levels are at 20%, 40%, 60%, 80%, and 95% of peak. The direction of the $B$-field in the plane of the sky is shown by a series of vectors at every position where a measurement of the polarized flux above the 2 $\sigma$ level was achieved. The plotted $B$-vectors are perpendicular to the direction of the polarization observed, and the length of each $B$-vector is proportional to the percentage polarization, such that a vector of length 20 represents a percentage polarization of 1%. The vectors are plotted on a grid spacing equal to the diameter of the JCMT beam, so each vector is independent.

Fig. 2.—Dust continuum emission at $\lambda$850 $\mu$m from the L183 prestellar core, with vectors of the inferred $B$-field direction overlaid. Details are the same as in Fig. 1.

Fig. 3.—Dust continuum emission at $\lambda$850 $\mu$m from the L43 prestellar core, with vectors of the inferred $B$-field direction overlaid. Contour levels are at 20%, 40%, 60%, and 80% of peak. Other details are the same as in Fig. 1.

Those data that were taken during unstable periods were seen to generate only noise, whereas all data taken during stable periods produced consistent results and were co-added to produce the maps shown here. During earlier observing runs with SCUBAPOL on 1998 February 13 and 14 and March 2 and 4 (UT), when it was operating only in single-pixel mode, we observed the central peak positions of the same three sources. We found that the current results agreed to within the errors with these previous measurements, confirming the repeatability of our results.

3. RESULTS

Figures 1, 2, and 3 present the results of our observations. In each case the Stokes $I$ map of dust emission is shown as a

(L1544) from Hawaiian Standard Time 01:30 to 09:30 (UT 11:30±19:30). SCUBA was used in conjunction with the polarimeter SCUBAPOL in the 16 position jiggling mode to produce a fully sampled $2.3$ image (Holland et al. 1999).

The observations were carried out while using the secondary mirror to chop $120^\circ$ in azimuth at around 7 Hz and synchronously to detect the signal, thus rejecting "sky" emission. The method of observation used was to make a full 16-point jiggle map (to produce a Nyquist-sampled map), with an integration time of 1 s per point, in each of the “left” and “right” beams of the telescope (the two beams are produced by the chopping secondary). This process was repeated at each position of the polarimeter half-wave plate. Then the half-wave plate was rotated to the next position, in steps of 22.5. Sixteen such positions thus constitute a complete revolution of the half-wave plate, representing 512 s of on-source integration, which takes about 12 minutes, including overheads (see Greaves 1999 and Greaves et al. 2000, for a description of SCUBAPOL). This process was then repeated several times—14 for L183, 15 for L43, and nine for L1544. The instrumental polarization (IP) of each bolometer was measured on the planets Uranus and Saturn and subtracted from the data before calculating the true source polarization. The mean IP was found to be $0.93\% \pm 0.27\%$. The observations were repeated with a slight offset in each case so that the three bolometers with significantly above-average noise could be removed without leaving areas of the map with no data. The atmospheric opacity at 225 GHz was monitored by the radiometer located at the Caltech Submillimeter Observatory. The opacity at 225 GHz was 0.06 during the L43 and L183 observations and 0.07 during the L1544 observations, typical of fairly good conditions at the site and corresponding to a zenith atmospheric transmission at 850 $\mu$m of about 80%.

Subsets of the data were reduced separately, and it was seen that atmospheric stability, rather than just transparency, was the limiting factor to the repeatability of the results obtained.
gray scale with contours overlaid. The direction of $B$ in the plane of the sky is shown by a series of vectors at every position where a measurement of the polarized flux above the 2 $\sigma$ level was achieved. Most vectors have a much higher signal-to-noise ratio than this, up to a maximum of 12 $\sigma$, with a mean of $\sim 5 \sigma$ across all three sources. The 2 $\sigma$ lower cutoff implies a maximum uncertainty in any given position angle of $\pm 14^\circ$. Note that we refer to these as magnetic field vectors, but they are not true vectors because they have a 180$^\circ$ directional ambiguity. The plotted $B$-vectors are perpendicular to the direction of the polarization observed, in accord with all of the various paramagnetic relaxation mechanisms of grain alignment by interstellar magnetic fields (e.g., Purcell 1979), and the length of each $B$-vector is proportional to the percentage polarization. Hence we are making the assumption that the polarization we are mapping traces the magnetic field direction. Given this reasonable assumption, we deduce the field direction in each source. The scale is such that a vector of length 2$^\circ$ represents a percentage polarization of 1%. The vectors are plotted on a grid spacing equal to the diameter of the JCMT beam so that each vector is independent.

3.1. L1544

Figure 1 shows our observations of the L1544 core, where we follow the naming convention of Benson & Myers (1989) and refer to the only known prestellar core in the larger dark cloud L1544 as the L1544 core. Our 850 $\mu$m data give core FWHM dimensions of $\sim 110^\prime \times 60^\prime$, with the minor axis at a position angle of $52^\circ \pm 5^\circ$ (all angles are measured north through east). The core is at a distance of 140 pc, and we have previously measured its mass to be $3.2 M_\odot$ (Ward-Thompson et al. 1999). Benson & Myers (1989) found that $\Delta V = 0.3$ km s$^{-1}$, which implies a virial mass of $\sim 1.7 M_\odot$. Hence this core appears to be gravitationally bound. Furthermore, recent spectroscopic observations show that the core appears to be contracting, although it is not apparently undergoing free-fall collapse (Tafalla et al. 1998). The weighted mean position angle of the magnetic field, averaged over the eight positions, is $23^\circ \pm 2^\circ$. Hence we see that the mean magnetic field direction is not along the minor axis of the prestellar core but at an angle of $29^\circ \pm 6^\circ$ to the minor axis and that the field appears to be fairly uniform. There is also some evidence that the percentage polarization decreases toward the peak of the source—this is discussed further in § 4.

There has been some recent debate about the nature of the physical processes that are currently determining the evolution of L1544. Ward-Thompson et al. (1999) showed that L1544 has a radial density profile that is consistent with that predicted by ambipolar diffusion theory, while noting some inconsistencies in the apparent timescales. Williams et al. (1999) claimed a discrepancy between the observed infall motions and the predictions of ambipolar diffusion theory. Subsequently, Ciolek & Basu (2000) have shown that in fact the ambipolar diffusion model can be fine-tuned to explain these motions. However, this model still requires that the magnetic field lies parallel to the minor axis of the core, and our observations disagree with this.

3.2. L183

Figure 2 shows our observations of the L183 core, where we once again refer to the only known starless core in the L183 dark cloud simply as the L183 core (it should be noted, however, that the L183 cloud is sometimes also referred to as L134N). Our 850 $\mu$m data give core FWHM dimensions of $\sim 120^\prime \times 60^\prime$ (although this is not so clearly defined, since the overall source extent north-south is greater than the SCUBA field of view), with the minor axis at a position angle of $80^\circ \pm 5^\circ$. The core is at a distance of 150 pc, and we measured its mass to be $\sim 1.3 M_\odot$ (Ward-Thompson et al. 1999). It has previously been seen that this core has $\Delta V(NH_2) = 0.24$ km s$^{-1}$ (Benson & Myers 1989), implying a virial mass of $\sim 1.2 M_\odot$. Hence this core also appears to be gravitationally bound.

The weighted mean position angle of the magnetic field, averaged over the 16 positions, is $46^\circ \pm 2^\circ$. Thus, the mean magnetic field is not parallel to the minor axis of the prestellar core but at an angle $34^\circ \pm 6^\circ$ to it, very similar to the situation observed in L1544. Once again, the magnetic field direction is fairly constant, and all variations are consistent with measurement uncertainties. Here, also, there is some evidence for the percentage polarization to decrease at the highest intensities (see § 4).

3.3. L43

Figure 3 illustrates our observations of the starless core in the L43 dark cloud. The X850 $\mu$m data give the core FWHM dimensions to be $\sim 100^\prime \times 60^\prime$, with its minor axis at position angle $37^\circ \pm 5^\circ$. It lies at a distance of 170 pc, and our separate SCUBA observations imply that its mass is $\sim 4 M_\odot$. Benson & Myers (1989) found that $\Delta V = 0.4$ km s$^{-1}$, which gives a virial mass of $\sim 2.1 M_\odot$, once again apparently showing that it is gravitationally bound. However, this is a more complicated region than the others. Figure 3 shows a second core at the western edge of the SCUBA field of view. There is a classical T Tauri star, RNO 91, embedded in this second core (Cohen 1980) and a molecular outflow centered on this source (Mathieu et al. 1988).

Study of the prestellar core in the center of the field shows a general area of roughly uniform polarization at position angle roughly 170$^\circ$ extending from the center of the core to the north. However, to the south and west of the core center, there is an area of vectors with position angle roughly 140$^\circ$. Moving still further to the west, the $B$-field appears to turn smoothly through an angle of roughly 90$^\circ$ until it has a position angle of $233^\circ \pm 4^\circ$ ($=53^\circ \pm 4^\circ$) at the position of RNO 91 at the western edge of the field.

We interpret this as follows: The outflow from RNO 91 is known to have cleared a cavity to the south of the source, and the southern edge of the prestellar core forms part of the cavity wall (Bence et al. 1998). Hence we believe that the $B$-field we observe in the southern and western parts of the prestellar core has in all probability been affected by the interaction with the outflow and lies roughly parallel to the cavity wall. However, away from the influence of the outflow, in the northern part of the prestellar core, the $B$-field we observe is more likely to represent the initial unperturbed field direction in the prestellar core. If this is the case, then the weighted mean $B$-field, averaged over these nine vectors, has a position angle $173^\circ \pm 2^\circ$, and the angle between the $B$-field and the core minor axis is $44^\circ \pm 6^\circ$. This is similar to the angle offset we observe in each of the other two cores. However, some caution must be attached to this estimate, since at the core center itself the percentage polarization is very low. In fact, the L43 prestellar core shows the clearest evidence for depolarization toward the peak of the core (see next section for discussion).

We also note that the magnetic field we observe in the RNO 91 region is perpendicular to the elongation axis of the edge-on circumbinary disk around RNO 91 that was discovered by the optical polarimetry observations of Scarrott, Draper, & Tadhunter (1993). However, if this disk originally collimated the bipolar outflow from this source, then the outflow must have
subsequently turned through almost 90° in breaking out of the cloud, as it is now seen to extend to large distances in an almost north-south direction (Bence et al. 1998).

4. DISCUSSION AND CONCLUSIONS

Theoretical models make predictions about the strength and geometry of magnetic fields that can be tested by observations. A crucial parameter in any theory or simulation of the structure and evolution of magnetic clouds is the ratio of thermal to magnetic pressures, $\frac{b}{r}$ (e.g., Ostriker, Gammie, & Stone 1999; Crutcher 1999). For example, Ostriker et al. (1999) follow the evolution of an initially uniform medium for various values of $\frac{b}{r}$ subjected to perturbations. For $\frac{b}{r} > 1$, turbulence dominates and the field lines become heavily tangled.

In the magnetically dominated case ($\frac{b}{r} \ll 1$), clouds form when material streaming along field lines (when the field geometry is uniform, without small-scale random variations) forms structures that are elongated preferentially perpendicular to the magnetic field. Most such models of the evolution of self-gravitating molecular cores supported by magnetic fields (e.g., Ciolek & Mouschovias 1994; Li & Shu 1996) predict that the cores should be oblate spheroids with minor axes parallel to the magnetic field direction.

The cores then evolve by the process of ambipolar diffusion, in which the neutral gas diffuses through the ionized component, which is held static by the magnetic field. However, simulations show that the magnetic field need not always be perpendicular to the elongation. If $\frac{b}{r} = 0.1 \rightarrow 1$, significant deviations are often found (Ostriker et al. 1999), although the initially uniform magnetic field remains the dominant component.

We have mapped the 850 $\mu$m polarization in three prestellar cores, L1544, L183, and L43, and used these measurements to infer the magnetic field geometries of these objects. In L1544 and L183, as well as in the region of L43 that we believe to be undisturbed by the nearby outflow, we see relatively uniform polarizations, leading us to infer a uniform magnetic field direction in each case. By comparison with the above-mentioned models, this suggests that those models that assume $\frac{b}{r} \leq 1$ are applicable to these regions (e.g., Ciolek & Mouschovias 1994; Li & Shu 1996; Ciolek & Basu 2000). Our observation in each case of an offset between the position angle of the $B$-field and the minor axis of each core appears to suggest that $\frac{b}{r} > 0.1$ (see Ostriker et al. 1999).

Some level of depolarization is observed toward the peak of each prestellar core. A similar depolarization effect was seen in OMC-3 by Matthews & Wilson (2000). This may indicate that the field has a small-scale structure below our resolution limit, causing the observed percentage polarization to decrease. If this is the case, then we can estimate the amount by which the random component diverges from the (larger) uniform component. Following Hildebrand & Dragovan (1995), we estimate that if the amount of depolarization is up to a factor of $\sim 2$, as we observe, then the small-scale random field could diverge from the ordered field by up to $\sim 35\%$. However, given the relatively high levels of polarization that we still observe at the core peaks, we believe that this is an upper limit. The alternative explanation for depolarization is that in denser regions, the number of collisions increases and hence the grain alignment efficiency decreases. We favor the latter explanation because we do not see the polarization direction varying, suggesting that the uniform ordered $B$-field component is still dominant, in agreement with our above deduction that $\frac{b}{r} < 1$.

Recent ISOCAM observations of prestellar cores seen in absorption at 7 and 15 $\mu$m have found that a number of cores, including L1544, have very sharply defined edges (Bacmann et al. 2000). From a comparison with various ambipolar diffusion models, Bacmann et al. concluded that only cloud cores that are highly magnetically subcritical can initially develop such sharp edges. For example, the best-fit model to the ISOCAM data of L1544 has $\frac{b}{r} \sim 0.08$ initially (see Ciolek & Mouschovias 1995), in apparent contradiction with the findings of this Letter. On the other hand, the model of L1544 proposed by Ciolek & Basu (2000) that has an initial $\frac{b}{r} \sim 0.2$, in better agreement with our present conclusions, cannot explain the ISOCAM data. Similarly, the models of Ostriker et al. (1999) cannot simultaneously explain the polarization data in this Letter (requiring $\frac{b}{r} > 0.1$) and the large density contrasts associated with prestellar cores (suggesting $\frac{b}{r} < 0.1$).

Hence our comparison of the observations and theoretical results leads us to conclude that no current model of magnetically regulated star formation can apparently account for all of the existing observations.

J. M. K. wishes to acknowledge PPARC for studentship support. R. M. C. is partially supported by National Science Foundation grant AST 98-20641 to the University of Illinois. We would also like to thank the JCMT telescope operators for their assistance during these observations and Tim Jenness for assistance with the software.

REFERENCES

André, P., Ward-Thompson, D., & Motte, F. 1996, A&A, 314, 625
Bacmann, A., et al. 2000, A&A, in press
Beichman, C. A., et al. 1986, ApJ, 307, 337
Bence, S. J., et al. 1998, MNRAS, 299, 965
Benson, P. J., & Myers, P. C. 1989, ApJS, 71, 89
Ciolek, G. E., & Basu S. 2000, ApJ, 529, 925
Ciolek, G. E., & Mouschovias, T. Ch. 1994, ApJ, 425, 142
Cohen, M. 1990, AJ, 85, 29
Crutcher, R. M. 1999, ApJ, 520, 706
Goodman, A. A. 1996, in ASP Conf. Ser. 97, Polarity of the Interstellar Medium, ed. W. G. Roberge & D. C. B. Whittet (San Francisco: ASP), 325
Greaves, J. 1999, The SCUBA Polarimeter User’s Guide, Version 4 (Hilo: JAC)
Greaves, J. S., et al. 2000, in Imaging at Radio through Submillimeter Wave-lengths, ed. J. Mangum & S. Radford (San Francisco: ASP), in press
Hildebrand, R. H., & Dragovan, M. 1995, ApJ, 450, 663
Holland, W. S., et al. 1999, MNRAS, 303, 659
Li, Z.-Y., & Shu, F. H. 1996, ApJ, 472, 211
Mathis, R. D., et al. 1988, ApJ, 330, 385
Matthews, B. C., & Wilson, C. D. 2000, ApJ, 531, 868
Ostriker, E. C., Gammie, C. F., & Stone, J. M. 1999, ApJ, 513, 259
Purcell, E. M. 1979, ApJ, 231, 404
Scarrott, S. M., Draper, P. W., & Tadman, C. N. 1993, MNRAS, 262, 306
Tafalla, M., et al. 1998, ApJ, 504, 900
Ward-Thompson, D., et al. 1994, MNRAS, 268, 276
Ward-Thompson, D., Motte, F., & André, P. 1999, MNRAS, 305, 143
Williams, J. P., Myers, P. C., Wilner D. J., & Di Francesco, J. 1999, ApJ, 513, L61