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simultaneously with previous ISO/CAM data.

measured cloud cores and conclude that no current model can explain these observations
to the core minor axis. We briefly compare our results with published models of M8-

star, whereas in the northern half the field appears less disordered and has an angle of

that is parallel to the wall of a cavity produced by a CO outflow from a nearby T Tauri

the cores, the L13-B field appears to have been influenced in the southern half, such

The observed polarizations in all the objects appear smooth and fairly uniform. In

magnetic fields in the plane of the sky were mapped from the polarization directions.

emission from dust. Linear polarizations at the vicinity of more independent positions

Bouvier et al. 2009. The observed trends about the way in which the magnetic field geometry affects the star

We present the first published maps of magnetic fields in protostellar cores, to test

ABSTRACT

France

CEA, DSM, DAMIA, Service d’Astrophysique, C.E. Saclay, 91191 Gif-sur-Yvette Cedex

and

Joint Astronomy Center, 660 N. A‘ohoku Place, University Park, Hilo, Hawaii 96720

S. Greaves and W. S. Holland

M. Calvet

D. Ward-Thompson and D. Myr

First Observations of the Magnetic Field Geometry in Protostellar Cores
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 by which stars are formed. Observations of the geometry of magnetic fields in molecular clouds appear therefore to be essential to a full understanding of the star formation process. Submillimetre 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 submm 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 which are believed to be gravitationally bound, but have not yet formed a central hydrostatic protostar.

Myers and co-workers (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 submillimetre continuum emission from starless cores to ascertain their morphologies and densities and named the most centrally condensed objects “pre-protostellar” (or “pre-stellar” for brevity) cores. André, Ward-Thompson & Motte (1996) carried out a detailed study of the pre-stellar core L1689B to compare it to 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 millimetre continuum emission from a larger number of pre-stellar 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 paper we present the first published submm continuum polarization observations of pre-stellar cores, which were carried out to test the predictions of theoretical models.
2. Observations

Submillimetre continuum polarimetry observations at $\lambda850$ $\mu$m were carried out using the SCUBA (Submillimetre Common User Bolometer Array) camera on the James Clerk Maxwell Telescope (JCMT)$^1$ on Mauna Kea, Hawaii, on the mornings of 1999 March 15 (L183 & L43) and September 15 (L1544) from HST 01:30 to 09:30 (UT 11:30 to 19:30). SCUBA was used in conjunction with the polarimeter SCUBAPOL, in the 16-position jiggling mode to produce a fully sampled 2.3 arcmin image (Holland et al. 1998).

The observations were carried out while using the secondary mirror to chop 120 arcsec in azimuth at around 7 Hz and synchronously to detect the signal, thus rejecting ‘sky’ emission. The method of observing used was to make a full 16-point jiggles map (to produce a Nyquist sampled map), with an integration time of 1 second per point, in each of the ‘left’ and ‘right’ beams of the telescope (the two beams are produced by the chopping secondary). This process is repeated at each position of the polarimeter half-wave plate. Then the half-wave plate is rotated to the next position, in steps of 22.5°. 16 such positions thus constitute a complete revolution of the half-wave plate, representing 512 seconds 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 9 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±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 $\lambda850$ $\mu$m of about 80%.

Subsets of the data were reduced separately and it was seen that atmospheric stability, rather than purely transparency, was the limiting factor to the repeatability of the results obtained. 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, when it was operating only in single-pixel mode, on 1998 February 13th & 14th, and March 2nd & 4th (UT), we observed the central peak positions of the same three sources. We found the current results agreed to within the errors with these previous measurements, confirming the repeatability of our results. Pointing and focussing were checked using the bright sources Uranus and IRAS16293 for L183 and L43, and CRL618 for L1544, and the pointing was found to be good to $\sim$1-2 arcsec throughout.

$^1$JCMT is operated by the Joint Astronomy Center, 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 & Westfield College, London.
3. Results

Figures 1-3 present the results of our observations. In each case the Stokes I map of dust emission is shown as a grey-scale with contours overlaid. The direction of \( \mathbf{B} \) 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° 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 is tracing 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 arcsec 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.

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 pre-stellar core in the larger dark cloud L1544 as the L1544 core. Our \( \lambda 850 \mu \text{m} \) data give core full width at half maximum (FWHM) dimensions of \( \sim 110 \times 60 \) arcsec, with the minor axis at a position angle of 52\( \pm 5^\circ \) (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 \( 3.2M_\odot \) (Ward-Thompson et al. 1999). Benson & Myers (1989) found that \( \Delta V(NH_3) = 0.3 \text{ km s}^{-1} \), 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 8 positions, is 23\( \pm 2^\circ \). Hence we see that the mean magnetic field direction is not along the minor axis of the pre-stellar core, but at an angle of 29\( \pm 6^\circ \) to the minor axis, and the field appears to be fairly uniform. There is also some evidence that the percentage polarization decreases towards the peak of the source – this is discussed further in section 4 below.

There has been some recent debate about the nature of the physical processes which are currently determining the evolution of L1544. Ward-Thompson et al. (1999) showed that L1544 has a radial density profile which is consistent with that predicted by ambipolar diffusion theory, whilst noting some inconsistencies in the apparent time-scales. 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 $\lambda$850 $\mu$m data give core FWHM dimensions of $\sim$120×60 arcsec (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±5°. 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 $\Delta V(NH_3) = 0.24$ 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±2°. Thus, the mean magnetic field is not parallel to the minor axis of the pre-stellar core, but at an angle 34±6° 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 section 4).

3.3. L43

Figure 3 illustrates our observations of the starless core in the L43 dark cloud. The $\lambda$850 $\mu$m data give the core FWHM dimensions to be $\sim$100×60 arcsec, with its minor axis at position angle 37±5°. 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 centred on this source (Mathieu et al. 1988).

Study of the pre-stellar core in the centre of the field shows a general area of roughly uniform polarization at position angle roughly 170° extending from the centre of the core to the north. However, to the south and west of the core centre there is an area of vectors with position angle roughly 140°. Moving still further to the west, the B-field appears to turn smoothly through an angle of roughly 90° until it has a position angle of 233±4° ($=53±4°$) 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 pre-stellar core forms part of the cavity wall (c.f. Bence et al. 1998). Hence we believe that the B-field we observe in the southern and western parts of the pre-stellar 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 pre-stellar core, the B-field we observe is more likely to represent the initial unperturbed field direction in the pre-stellar core. If this is the case, then the weighted mean B-field, averaged over these 9 vectors, has a position angle 173±2°, and the angle between the B-field and the core minor axis is 44±6°. 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 centre itself the percentage polarization is very low. In fact the L43 pre-stellar core shows the clearest evidence for depolarization towards the core peak (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 circumstellar disk around RNO 91 that was discovered by the optical polarimetry observations of Scarnott, 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, $\beta$ (c.f. Ostriker et al. 1999; Crutcher 1999). For example, Ostriker et al. (1999) follow the evolution of an initially uniform medium for various values of $\beta$ subjected to perturbations. For $\beta > 1$ turbulence dominates and the field lines become heavily tangled.

In the magnetically dominated case ($\beta << 1$), clouds form by material streaming along field lines, so that structures that are elongated preferentially perpendicular to the magnetic field are formed and the field geometry is uniform, without small-scale random variations. 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 ionised 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 $\beta = 0.1 \rightarrow 1$, then significant deviations are often found (Ostriker et al. 1999), although the initially uniform magnetic field remains the dominant component.
We have mapped the $\lambda850\ \mu m$ polarization in three pre-stellar cores, L1544, L183 & 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 which assume $\beta \leq 1$ 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 $\beta > 0.1$ (c.f. Ostriker et al. 1999).

Some level of depolarization is observed towards the peak of each pre-stellar core. A similar depolarization effect was seen in OMC-3 by Matthews & Wilson (2000). This may be indicating that the field has 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 $\sim 35^\circ$. However, given the relatively high levels of polarization that we still observe at the core peaks, we believe 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 favour 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 $\beta < 1$.

Recent ISOCAM observations of pre-stellar cores seen in absorption at 7 & 15 $\mu m$, have found that a number of cores, including L1544, have very sharply defined edges (Bacmann et al. 2000). From comparison with various ambipolar diffusion models, Bacmann et al. concluded that only cloud cores which are highly magnetically subcritical initially can develop such sharp edges. For example, the best fit model to the ISOCAM data of L1544 has $\beta \sim 0.08$ initially (c.f. Ciolek & Mouschovias 1995), in apparent contradiction with the findings of this paper. On the other hand, the model of L1544 proposed by Ciolek & Basu (2000) which has an initial $\beta \sim 0.2$, 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 paper (requiring $\beta > 0.1$) and the large density contrasts associated with pre-stellar cores (suggesting $\beta < 0.1$).

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.

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REFERENCES


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Fig. 1.— Dust continuum emission at $\lambda 850 \mu m$ from the L1544 pre-stellar core. The Stokes I map is shown as a grey-scale with contours overlaid. Contour levels are at 20, 40, 60, 80 & 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 2 arcsec 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 pre-stellar core, with vectors of the inferred B-field direction overlaid. Details as in Figure 1.

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