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Letter to the Editor

Twisted magnetic field lines around protostars

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Abstract. Polarized dust emission from six star-forming cloud cores has been detected, at wavelengths of 450 to 1100 μm. The data are used to measure net magnetic field directions as a function of beam size, and in two sources the field is found to twist through very large angles (60–70°). For the low-mass protobinary IRAS16293-2422, one field direction is along the circumbinary disk, while another is aligned between the two bipolar outflows. This is the first observational evidence of bent field lines around protostars. For the high-mass W75N source, the data indicate a centrally contracted field. The dust core occupies the most compressed part of the field, and the field lines are bent by large angles, $> 45°$.

In the highest angular resolution observations ($8''$ beam at 450 μm), the deduced magnetic field direction is *parallel* to the outflow axis, in all three sources observed. This suggests the highest-resolution observations may be tracing the components of the magnetic field that constrain the outflowing gas.

Key words: polarization – stars: formation – ISM: magnetic fields

1. Introduction

Magnetic fields are thought to be important in star formation, especially in braking processes which move angular momentum outwards, and in the collimation of jets and bipolar outflows. It is now possible to detect the magnetic fields in star-forming cores using far-infrared or submillimetre polarimetry (e.g. Flett & Murray 1991). Elongated dust grains are partially aligned by the field and consequently their emission is linearly polarized. The average direction of the field, within the telescope beam and in the plane of the sky, is perpendicular to the position angle of the polarization.

Many models exist predicting the magnetic field structure around protostars (e.g. Henriksen & Valls-Gabaud 1994; Newman et al. 1992; Shu et al. 1995). A feature of many of these models is that the field lines are *twisted*. For example, a linear field in the ambient cloud material may be wound up in a circumstellar disk, and then twist through a right angle to emerge along the outflow axis. So far, there is no direct evidence for such twisted field lines. We have therefore made polarization measurements of a sample of star-forming cores, to look for changes in field orientation over different size scales.

The six sources selected have all previously been detected in 800 μm polarimetry at the James Clerk Maxwell Telescope (JCMT). We have now detected five of the sources at 1100 μm, and three of the brighter objects at 450 μm. In this Letter, we present the evidence for twisted magnetic fields in two of the sources, and compare the results to models of magnetized star-forming cores.

2. Observations

The observations were made in February and July 1995, at the JCMT, located on Mauna Kea, Hawaii. The data were obtained using the Aberdeen/QMW polarimeter (Murray et al. 1992; Murray 1991) and the continuum receiver UKT14 (Duncan et al. 1990). The polarimeter half-wave plate was stepped at 22.5° intervals around 360°, and the resulting sinusoidally modulated signal was analysed to find the polarization (Nartallo 1995). Integration times were 16s per waveplate position, with typically 10 waveplate cycles of 360° needed to detect the polarization.

The 450 μm data were obtained in July 1995, during a period of excellent weather when the 450 μm zenith sky opacity was only ~ 0.6 (about 0.75 mm of precipitable water vapour). The 1100 μm data from February 1995 were observed with PWV $\sim$ 1.5–3 mm, and 1100 μm sky opacities of ~ 0.2. During the runs, instrumental polarization was measured on Mars (assumed to be unpolarized), and subtracted in the reduction. The IP levels were $1.93 \pm 0.27\%$ and $1.73 \pm 0.07\%$ at 450 and 1100 μm respectively. The telescope beam sizes were $8''$ and $19''$ at these wavelengths (full-width at half-power), while the beam size for previous 800 μm observations was $14''$. The telescope pointing is accurate to $2''$ or better.

3. Results

The polarimetry results at 450 and 1100 μm are presented in Table 1, together with previous JCMT 800 μm data. For each source, the position angle of the polarization, θ, has been used to derive the magnetic field direction, $\theta_B = \theta \pm 90°$, within

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Table 1. Submillimetre polarimetry results at 450 and 1100 μm, together with previously published data, primarily at 800 μm. The first three cores contain low or intermediate mass stars, and the second three are high-mass sources. The percentage polarization and associated position angle are given by p and θ respectively; p values and θ errors have been corrected for bias effects (Wardle & Kronberg 1974). The mean magnetic field angle is given by $\bar{\theta}_B$, with a $\pm 1\sigma$ range from the measurements.

source	R.A.,Dec. (1950)	distance (pc)	wavelength (μm)	p (%)	θ ($^\circ$)	$\bar{\theta}_B$ ($^\circ$)
IRAS16293-2422	16h 29m 21.05s, –24° 22′ 15.5″	160	450	1.83 ± 0.47	173 ± 7	110 ± 30
			800[a]	1.44 ± 0.40	62 ± 8	
			1100	1.01 ± 0.24	4 ± 7	
NGC1333-IRAS4A	03h 26m 04.8s, +31° 03′ 13.6″	350	800[b]	3.8 ± 0.6	144 ± 9	54 ± 8
			1100[c]	4.91 ± 0.42	142 ± 2	
S106-IR	20h 25m 34.3s, +37° 12′ 50.0″	600	800[d]	3.14 ± 0.78	173 ± 7	73 ± 11
			1100	2.68 ± 0.71	152 ± 7	
W75N	20h 36m 50.0s, +42° 26′ 58.0″	2000	450	2.02 ± 0.63	127 ± 9	172 ± 32
			800[e]	0.7 ± 0.24	55 ± 5	
			1100	∼0.30 ± 0.28	∼63 ± 22	
W3-IRS5	02h 21m 53.2s, +61° 52′ 21.0″	2300	800[f]	0.49 ± 0.31	47 ± 18	149 ± 12
			1100	1.75 ± 0.58	70 ± 9	
NGC7538-IRS11	23h 11m 36.8s, +61° 10′ 37.0″	2700	450	2.39 ± 1.06	83 ± 13	161 ± 13
			800[g]	2.5 ± 0.2	58 ± 2	

References: [a] Greaves et al. (1997), see also Flett & Murray (1991); [b] mean of values from Minchin et al. (1995), Tamura et al. (1995); [c] our result, see also Tamura et al. (1995); [d] Holland et al. (1996); [e] Vallée & Bastien (1995), flux peak position; [f] Greaves et al. (1994); [g] Minchin & Murray (1994), see also Flett & Murray (1991).

each beam size used. The range of observed θ_B values is given in the last column of Table 1.

The observed polarization position angle is expected to exactly trace the net magnetic field orientation in the cores, since the submillimetre dust emission is optically thin, and therefore arises from all the grains along the line of sight. Thus, if θ changes in going from a small to a large beam size, there must be a net twist in the field within this larger beam. In particular, extended emission detected only in the larger beam must be associated with a different field direction, compared to more compact emission seen by both beams.

Such twists in the field are clearly seen in two of our sources, IRAS16293-2422 and W75N. In IRAS16293-2422, the difference in field orientation between 450 and 800 μm beam sizes is 69° ± 11°, and that between 800 and 1100 μm is 58° ± 11°. Remarkably, the field has twisted from an east-west orientation in the smallest beam, to a roughly SE-NW one, and then *back* again to E-W in the largest beam. This indicates a complex underlying field structure. In W75N, the orientation change from the 450 to the 800 μm beams is 72° ± 10°, and the field direction at 1100 μm is uncertain, but probably close to that at 800 μm.

For the other four sources in Table 1, θ changes by much less (≈ 10–25° between the 450, 800 and 1100 μm beams). These are more typical results — for example, a compilation of 800 and 1100 μm JCMT polarization results shows a mean position angle change of ≈ 18° between the two wavelengths. Thus the angle changes of 60–70° seen in IRAS16293-2422 and W75N are clearly exceptional. Small θ variations as a function of wavelength can occur for sources with mixed grain populations, but not with this magnitude (Greaves et al. 1998).

4. Discussion

4.1. The magnetic field around IRAS16293-2422

IRAS16293-2422 is a low-mass system containing two candidate protostars, separated by 5″ on the sky (Wootten 1989; Mundy et al. 1992). Our observations are centred on the MM1 source, which has most of the submillimetre flux (Tamura et al. 1993). There are two bipolar outflows in the system, at position angles of approximately 55° and 105° (Walker et al. 1988), of which the former (most highly collimated) is associated with MM1, and the latter perhaps with MM2 (Walker et al. 1992, but see Fukui et al. 1993).

The magnetic field direction at 800 μm is close to the major axis of the circumbinary envelope (Walker et al. 1992, and Fig. 1). This suggests that the two protostars may be magnetically linked through their surrounding material. A similar result has also been obtained from 3 mm polarimetry (Akeson & Carlstrom 1997). In contrast, the field seen at 450/1100 μm is at θ_B = 89° ± 6°, which is close to the bisecting lines between the two outflows, at an angle of (55°+105°)/2 = 80°. It is therefore tempting to identify field components near the outflow axes and the circumbinary disk plane. However, it is unclear what determines which field direction is seen in which beam size.

The data show, for the first time, some very large twists in the magnetic field around low-mass protostars. Such twists, of ∼ 90°, can occur where the field in the disk plane bends to

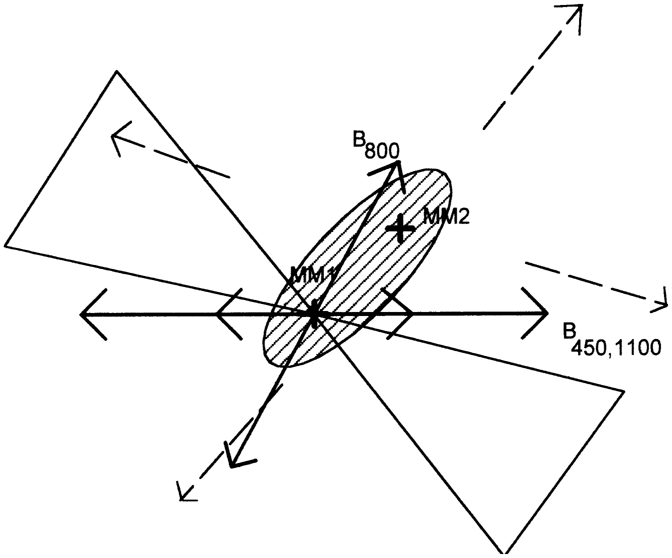

Fig. 1. Magnetic field orientations in IRAS16293-2422. The bold arrows represent the net magnetic field directions at 800 and 450/1100 μm, and the arrow lengths are equal to the FWHM beam sizes. The circumbinary disk (shaded) and outflow locations (solid lines and dashed arrows) are based on Walker at al. (1992, 1988), and the crosses mark the positions of the two protostars.

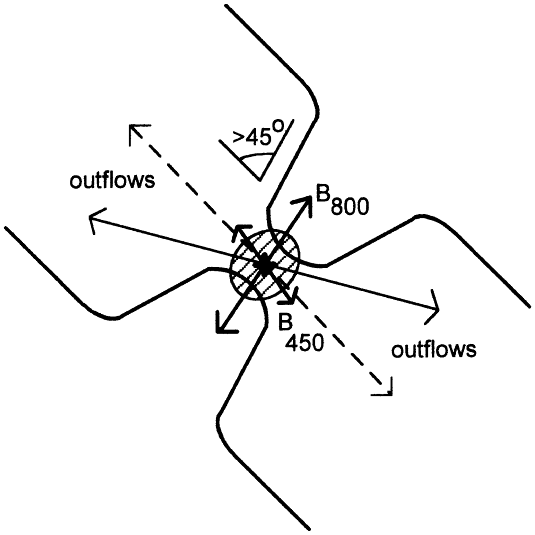

Fig. 2. A schematic diagram of the proposed field structure in W75N. The dense core (shaded) occupies the region where the field lines are most compressed. The field and outflow directions are shown as in Fig. 1; the outflow data are from Hunter et al. (1994).

emerge along the outflow, and this is the first evidence of such an effect. In addition, the scale on which the field is twisted in IRAS16293-2422 can be identified. The field orientation is different at $14''$ resolution, compared to $8''$ or $19''$, so significant twisting occurs over a region of size $\sim 14''$ (2000 au at 140 pc). This size scale is typical of protostellar envelopes (e.g André et al. 1993), and much larger than the sizes of the accretion disks (e.g. < 70 au for the protostar VLA1623, Pudritz et al. 1996). Thus the observed twisting occurs within the circumbinary envelope. This is consistent with models such as those of Henriksen & Valls-Gabaud (1994), where circumstellar magnetic fields follow large-scale streamlines.

4.2. A model for W75N

For W75N, our observations were centred on the source W75N-HII(B), which is thought to drive the outflow (Moore et al. 1991). The outflow system (Hunter et al. 1994) has two concentrations of material along axes at 45° and 75°, and thus consists either of two well collimated flows, or the two sides of a wider, hollow outflow.

A magnetic field model for W75N is sketched in Fig. 2. It is suggested that quasistatic contraction has occurred, pulling in the initially linear field lines, along with infalling gas and dust, into a flattened core (e.g. Nakano 1990). Magnetic flux is gradually lost, until it becomes subcritical, and the core collapses to form stars. Outflows emerge perpendicular to the core plane, along the symmetry axis of the field.

For W75N, the 450 μm beam appears to be tracing the straight field lines at the centre of the system, while the larger 800 and 1100 μm beams are dominated by the pulled-in field lines, so the net result is in the *perpendicular* direction (Fig. 2). The observed difference in the 450 and 800 μm orientations is $72 \pm 10°$, in reasonable agreement with the expected right angle, and the symmetry axis, at an angle of $\theta_B \approx 37°$, is aligned close to the outflow oriented at 45°. A requirement of the data is that the field lines must bend outwards by $> 45°$, relative to the central linear region, in order to produce a net SE-NW field at the longer wavelengths (Fig. 2). This may be a useful test for models of contracted fields.

In W75N, the core size is similar to that of the 450 μm beam, tracing the central linear part of the field. The beam FWHM is $8''$, and a five-point map made at 450 μm indicates a core diameter of $\sim 8''$. A similar result is found for the contracted field mapped in W3-IRS5 (Greaves et al. 1994), where the central part of the field occupies roughly the area of the $14''$ beam, and the core size is $13''$ (Oldham et al. 1994). These data indicate that the dense post-collapse core occupies the region where the field lines have contracted the most.

4.3. Magnetic collimation of outflows

The JCMT 450 μm observations have the highest angular resolution of any single-dish submillimetre polarimetric observations. For the three sources observed at 450 μm, we find that at $8''$ resolution, θ_B *is in all cases parallel to some part of the outflow system*. In IRAS16293-2422, the field direction at 450 μm is between the two outflow axes, while for W75N, the field is close to the axis of the NE-SW outflow lobe. In NGC7538-IRS11, the deduced field at 450 μm lies north-south, and the outflow lobes are offset north and south from the central object (Kameya et al. 1989), which suggests that this is the direction of the current outflow phase. Finally, we note that Akeson et al. (1996) have observed the proto-binary NGC1333-IRAS4A with 5″ resolution (at 3.4 mm) using the OVRO interferometer array. They measured the field directions at the two polarization peaks, and found fields aligned within $\sim 15^\circ$ of the two outflow axes (see Minchin et al. 1995).

In all these cases, the magnetic field on 5–8″ scales is aligned near an outflow axis, and for our three sources, the field direction is significantly different with a lower resolution. Thus, the high-resolution observations may be isolating *the field component that constrains the bipolar outflows*. Many models predict that outflow collimation takes place within a few au of the protostar itself (e.g. Shu et al. 1995), but our observations suggest that magnetic fields also influence the flow on much larger scales.

5. Conclusions

We have searched for evidence of twisted magnetic fields in six star-forming systems, and found twists of ≈ 60–70° in two sources, W75N and IRAS16293-2422. For the latter, the results give the first observational evidence for twisted fields around low-mass protostars. Such fields have been predicted in models of protostellar evolution. In the massive star-forming core W75N, the data support a model of contracted field lines, similar to that previously proposed for W3-IRS5 (Greaves et al. 1994). Finally, we have detected polarization in three sources at a high angular resolution (8″), and find that in all three cases the net field is aligned with some part of the outflow system. This suggests that the high-resolution data may reveal the field component that constrains the outflows.

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