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Magnetic Fields in Molecular Clouds

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Abstract.
Magnetic fields are believed to play an important role in the evolution of molecular clouds, from their large scale structure to dense cores, protostellar envelopes, and protoplanetary disks. How important is unclear, and whether magnetic fields are the dominant force driving star formation at any scale is also unclear. In this review we examine the observational data which address these questions, with particular emphasis on high angular resolution observations. Unfortunately the data do not clarify the situation. It is clear that the fields are important, but to what degree we don't yet know. Observations to date have been limited by the sensitivity of available telescopes and instrumentation. In the future ALMA and the SKA in particular should provide great advances in observational studies of magnetic fields, and we discuss which observations are most desirable when they become available.

1. Are Magnetic Fields Important?

Magnetic fields are believed to play an important role in the evolution of molecular clouds, and hence star formation. However, despite progess on both the observational and theoretical fronts in recent years, many questions remain to be answered. Fundamental questions include (1) what is the dominant mechanism driving star formation, magnetic fields or turbulence, and (2) how important are magnetic fields at different stages in the star formation process?

For most of the past two decades the prevailing picture for the evolution of a dense molecular cloud core to form a protostar has been one of "quasi-static" evolution of a strongly magnetised core through ambipolar diffusion, over a time scale $>>$ the free-fall time, t_{ff}, leading eventually to inside-out collapse onto the central region (Shu et al. 1987, 1999; Mouschovias & Ciolek 1999). Recently a new theory has emerged, where the molecular clouds themselves are short-lived phenomena (liftimes a few t_{ff} at most) and the star formation process is dynamical from the outset. In this picture supersonic turbulence is the dominant force in controlling the evolution of clouds and cores, and regulates the star formation rate (see reviews by Mac Low & Klessen 2003, Vázquez-Semadeni 2004, and reference therein).

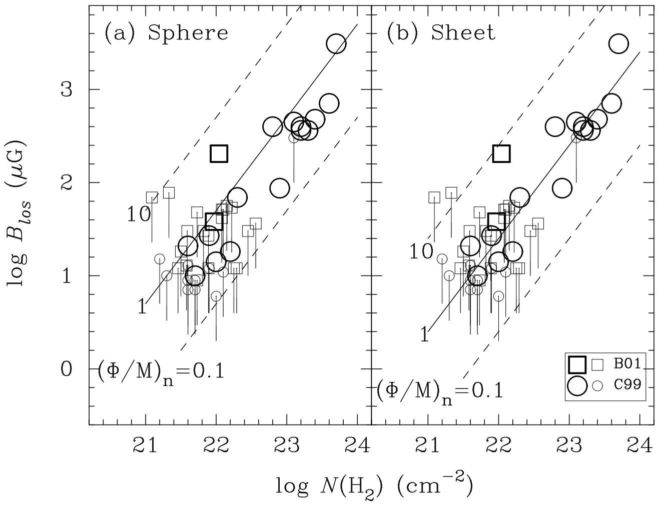

Figure 1. Magentic field strengths and column densities from Bourke et al. 2001 (B01) and Crutcher 1999 (C99). See Bourke et al. 2001 for details. This plots indicates that Zeeman measurements are consistent with molecular clouds being in an approximately critical state, $(\Phi/M)_n = 1$, or slightly supercritical (< 1), depending on the adopted geometry.

The quasi-static model implies that cloud cores should be strongly magnetically subcritical (i.e., static magnetic fields are strong enough to provide support against gravity for $t >> t_{ff}$). In addition to supercritical cores (where the magnetic field provides no support), the dynamical model is able to accommodate approximately critical or slightly subcritical cores, as they will quickly evolve into supercritical cores and collapse. However, measurements of magnetic field strengths (and hence magnetic flux-to-mass ratios) in cores, which are needed to discrimate between the two models, are very difficult to obtain. The only practical tool available for directly measuring the field strength is the Zeeman effect (Crutcher 1999, 2004). Unfortunately molecules that are sensitive to the Zeeman effect either have transitions that are too high in frequency (e.g., CN at 113.5 GHz) or are too weak (CCS at 22-46 GHz) for current instrumentation, or don't sample the densest gas in low-mass cores (OH at 1.6 GHz), to provide a large set of measurements of the field strength.

In the less dense regions of molecular clouds around the cores, where a number of Zeeman measurements have been made (mainly using OH), both with single dish radiotelescopes and interferometers, the results suggest that clouds are approximately critical (Figure 1; Bourke et al. 2001; Crutcher 1999, 2004; see also Myers & Goodman 1988), which does not seem to favour the quasi-static model of magnetic field support. However, measurements of field strengths in dense cores ($n \geq 10^5$ cm^{-3}) are required.

The direction and dispersion of polarization vectors tracing magnetic field lines can theoretically be used to discriminate between the quasi-static and turbulent models (Matthews et al. 2001, 2002, 2004; Matthews & Wilson 2002a,b; Henning et al. 2001; Wolf et al. 2003; Crutcher 2004). If the field is sufficiently strong then a small dispersion is predicted, and field lines should lie approximately parallel to a dense core's minor axis, or show an hourglass morphology if it has evolved toward the collapse phase, when observed with high angular resolution. In the turbulence driven model field lines may appear regular on the larger size scales traced by the filaments in which the cores are embedded, but are not expected to show any regular pattern on the size scale of the cores themselves. Of course, reality is never this simple. Observations of cores and filaments in polarized dust emission sometimes show the regular pattern expected in the strong field case, but with sufficient dispersion to imply that turbulence is important, and with mean direction close to but not parallel to the cores' minor axes, as expected in the quasi-static model (however, this last point can be explained as a projection effect - Basu 2000).

At present the data do not strongly support either model. In fact the data can be explained with either model with a sufficient number of caveats! Clearly real clouds and cores have both magnetic fields and turbulence, and the dominant mechanism may be region dependent, e.g., MHD turbulence on large scales and ambipolar diffusion on small scales. Until a large number of magnetic field measurements are made in the densest regions of cores, and the full three dimensional field structure of clouds and cores can be determined, deciding between the two will be difficult.

In the following sections we look in more detail at the observations that lead us to these conclusions, in particular those made with "high angular resolution", which for this field does not automatically imply interferometers. We also examine what future observations are required to make progress in this field.

2. Observational Overview - High Resolution Observations

Due to the difficultly in making magnetic field measurements with current interferometers, this section on high resolution observations of magnetic fields includes Zeeman and dust polarization measurements made with sub-arcminute beams on single dish telescopes (i.e., IRAM 30-m; JCMT 15-m).

Magnetic fields in molecular clouds can be probed by a number of means. The Zeeman effect has been used to determine the line-of-sight field strength (B_{los}) in thermal lines, both in emission and absorption (Crutcher 1999; Bourke et al. 2001; and references therein). Masers are also potential tools, but the uncertainty in determining the physical conditions and sizes of the masing regions make it difficult to interpret the results. Polarimetry of aligned dust grains is the other major observational technique, which can be used to map the morphology of the field in the plane of the sky, and to estimate the field strength (B_p) using the modified Chandrasekhar-Fermi (C-F) method (Ostriker et al. 2001; Padoan et al. 2001; Heitsch et al. 2001a). Studies have been conducted in both the near-infrared, the far-infrared, and more recently in the (sub)millimetre. As discussed in the following sections, each method has a number of shortcomings and full information on the 3D structure of magnetic fields in molecular clouds are lacking in most cases. Possible methods for obtain such information are discussed in §3.

2.1. Zeeman Measurements

Most observations of the Zeeman effect in molecular clouds have been performed using single dish telescopes observing the OH transitions at 1.6 GHz, with a few studies using the VLA. Other secure detections of the Zeeman effect have come from HI, CN and excited transitions of OH (Güsten et al. 1994).

High resolution Zeeman observations of the densest regions of nearby low mass cores are almost non-existent. CCS observations of the chemically evolved, heavily depleted starless core L1498 (Levin et al. 2001) and the chemically young L1521E (Shinnaga et al. 1999; see also Aikawa 2004) have been made with sub-arcminute resolution. Shinnaga et al. claim a detection with $B_{los} = 160 \pm 46\mu$G using the 45 GHz transition, and state that this value is larger than the critical value (which unfortunately they do not give). This result requires confirmation, preferably using other CCS transitions at lower frequencies.

The Zeeman effect has been observed in the CN 1-0 transition at 113 GHz with the IRAM 30-m ($23''$ beam) by Crutcher et al. (1999) toward four cores associated with the high mass star-forming regions OMC1, DR21OH and M17SW. As the *frequency offset* due to the Zeeman effect is *independent* of the line frequency, whereas the *Doppler broadened line width* is *proportional* to the line frequency, the ratio of the Zeeman effect to the line width decreases as the frequency of the line increases. This makes observations of the Zeeman effect at mm wavelengths much less sensitive than at cm wavelengths, hence the paucity of observations with this potentially rewarding transition. Because CN 1-0 consists of a number of hyperfine components with different Zeeman effects, the detections are fairly secure. Crutcher et al. conclude that the cores observed are supercritical by a factor 2–3.

VLA Zeeman observations with beam sizes $5 - 60''$ in the HI 21 cm and OH 18 cm transitions have been performed toward a number of high-mass star forming regions (e.g., W3 – Roberts et al. 1993; S106 – Roberts et al. 1995; DR21 – Roberts et al. 1997; NGC 2024 – Crutcher et al. 1999; M17 – Brogan et al. 1999, 2001; NGC 6334 – Sarma et al. 2000). In many cases it is claimed that the HI and/or OH emission is in fact tracing high density ($> 10^4$ cm^{-3}) gas in a PDR interface between the ionized and molecular regions. Line-of-sight field strengths up to 0.5 mG have been observed in most regions, with large variations across the mapped areas (Figure 2). In NGC 6334 the field actually changes sign, while in other regions it drops to 0 in places, indicating significant changes in direction of the field. This result, and the similar result in M17, could explain the lack of detection in single dish Zeeman observations in these sources (Bourke et al. 2001). In all these studies it is inferred that the magnetic field is either approximately critical (W3, S106, NGC 6334) or supercritical by a factor 2–3 (NGC 2024, M17). There is certainly no clear evidence for a subcritical cloud in any observations of the Zeeman effect alone.

2.2. Dust and Spectral Line Polarization

Some years ago it was hoped that polarized background starlight observed in the infrared would be a useful probe of the denser regions of molecular clouds, but the percentage polarization was not observed to increase as expected (Goodman et al. 1995). More recently the polarized thermal emission in the far-infrared and (sub)millimetre regions has been used to infer the field direction in the plane

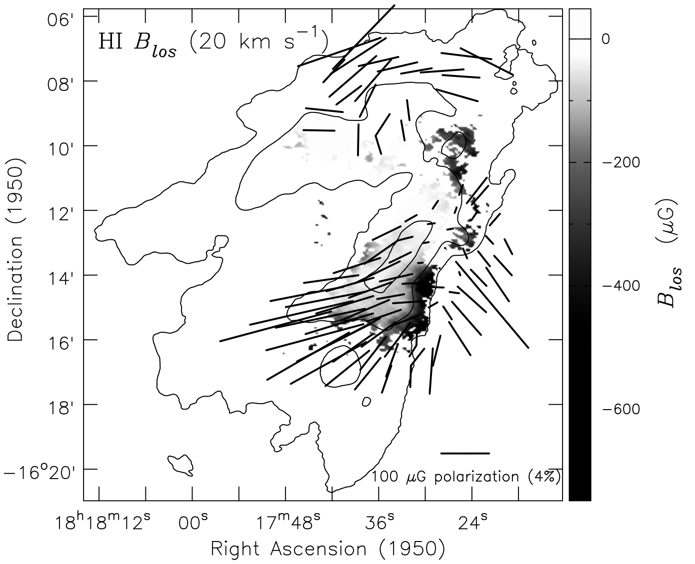

Figure 2. Greyscale image of the line-of-sight field strength B_{los} measured in the 20 km/s HI component toward M17SW with the VLA (Brogan et al. 2001). The contours represent the 21 cm continuum emission. The magnetic field direction in the plane of the sky is indicated with the superimposed 100 μm polarization vectors, rotated 90° (Dotson et al. 2000).

of the sky from a number of clouds and cores (Dotson et al. 2000; Davis et al. 2000; Matthews et al. 2001, 2002, 2004; Matthews & Wilson 2002a,b; Henning et al. 2001; Wolf et al. 2003; Crutcher et al. 2004). Interestingly these studies also find that the percentage polarization does not increase toward the regions of maximum intensity (and hence density). In fact a *decrease* in percentage polarization is observed in most cases. The likely explanation in most cases is poor grain alignment due to spherical grain growth ("bad grains" – Goodman et al. 1995; Lazarian et al. 1997; Padoan et al. 2001).

The far infrared observations of high mass star forming regions using the KAO have been discussed elsewhere (Dotson et al. 2000 and references therein). All the KAO maps show regular structures (but not necessarily uniform) with depolarization at the highest intensities. It would be useful to apply more recent analysis techniques to these data, for example the modified C-F method.

Two instruments have been used to obtain most of the (sub)millimetre results published at this time – the SCUBA polarimeter at 850 μm, and BIMA at 3 and 1 mm. Observations have also been made with OVRO (Akeson & Carlstrom 1997) and the 350 μm polarimeter HERTZ on the CSO (Schleuning et al. 2000; Houdé et al. 2002).

Matthews et al. (2004) have combined SCUBA and BIMA observations of Orion and Perseus (B1), comparing the large and small scale field directions. They find that in Orion the field direction in the cores is similar to that of the filaments in which they are embedded, but in B1 the cores show different orientations. The reason for these differences is unclear, but they could imply that B1 is globally supported by turbulence, with local density enhancements able to undergo collapse, whereas Orion is not turbulently supported (although its turbulence is "greater"), resulting in more ordered field lines on all scales (Heitsch et al. 2001b; Mac Low & Klessen 2003). The relevant physical parameters need to be evaluated to examine this (e.g., mass-to-flux ratio, turbulent line width, virial terms). A SCUBA map of the Serpens region, containing a number of protostars, was presented by Davis et al. (2000). In the NW cluster the field shows some degree of regularity, but in the presumably older SE there is a large dispersion in field direction between the protostars, possibly suggesting the field becomes less important at the core size scale as star formation progresses.

Recent mapping studies of individual low mass starless cores (Ward-Thompson et al. 2000; Crutcher et al. 2004) and protostars (Henning et al. 2001; Wolf et al. 2003; Valleé et al. 2003) have been made with SCUBA. All these results show depolarization at the highest intensities (Padoan et al. 2001). In starless cores the fields are uniform, but not aligned with the core minor axes, displaying offsets of up to 30°, and all cores are found to be supercritical (or at least are not clearly subcritical), with field strengths inferred using the modified C-F method ($B_p \sim$50-150 μG). In protostellar cores the fields do not appear to be as uniform (possibly due to outflow disruption), and no clear preferred orientation with respect to either the outflows or cores is evident, although there is some suggestion the field lines are either aligned parallel or perpendicular to the outflow axis on a case by case basis. Field strengths estimated via the modified C-F method are typically 100–200 μG, but unfortunately are not compared to the critical values.

Interferometric studies at mm wavelengths have been made with both OVRO (Akeson & Carlstrom 1997) and BIMA (Rao et al. 1998; Lai et al. 2002, 2003a), of both low and high mass protostars. As the OVRO observations only produced a couple of measurements per field, we concentrate on the BIMA results. Rao et al. (1998) observed Orion-KL at 3 and 1 mm with $\sim 5''$ beams. A relatively ordered field was observed except near the position of IRc2, where the field direction changed by 90°. This is explained as the effect of the outflow on the dust grains causing alignment due to streaming motions (the "Gold" effect – Lazarian 1997). Lai et al. (2002) observed NGC 2024 FIR 5 at 1 mm with $2''$ resolution. A uniform field was observed, with a slow change in position angle, which they modelled as due to an hourglass shaped morphology. They claim the pattern is due to contraction of the psuedo-disk perpendicular to the field (e.g., Galli & Shu 1993). Applying the modified C-F method they infer a field strength in the plane of the sky of $\sim$3.5 mG. This is extremely large compared to the Zeeman OH result of 65 μG for the line-of-sight component. If the field is not close to the plane of the sky, as these numbers would suggest, then the result could be explained as due to beam averaging of the OH data ($60''$) or the OH data does not trace the same high density region as the 1 mm dust emission. Another explanation is the modified C-F method is not applicable in this case.

Linear polarization of CO emission has been observed with BIMA toward the low mass protostar NGC 1333 IRAS 4A (Girart et al. 1999; Figure 3), and the high mass protostellar region DR21(OH) (Lai et al. 2003a). Girart et al. find that the dust polarization pattern toward IRAS 4A is consistent with a pinch (hourglass) configuration. Linear polarization of CO is detected mainly toward the redshifted outflow lobe. The polarization of spectral lines is predicted to be either parallel or perpendicular to the field, depending on a

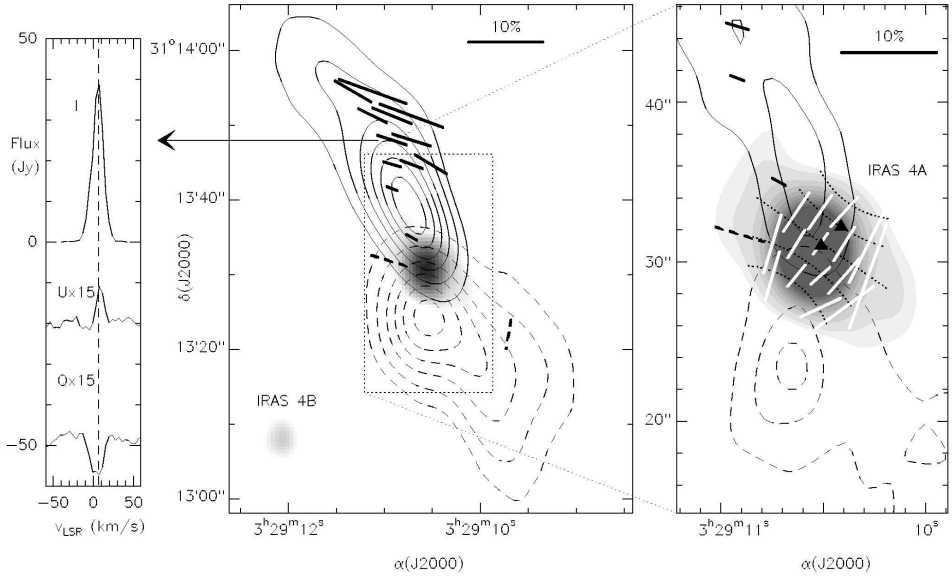

Figure 3. *Middle panel:* The greyscale shows the 1.3 mm dust emission from NGC 1333 IRAS 4 as observed with BIMA by Girart et al. (1999). Superimposed are contours of redshifted (solid) and blueshifted (dashed) integrated intensity of CO 2-1, and vectors showing the position angle of linearly polarized CO 2-1 emission. *Right panel:* A magnified map of the central region, with white vectors indicating the position angle of the dust polarization, and the dotted lines indicating a possible pinch magnetic configuration. *Left panel:* CO 2-1 spectra of Stokes I, U and Q averaged over the redshifted outflow lobe, with the cloud ambient velocity indicated.

number of factors (Goldreich & Kylafis 1982). Girart et al. argue that in this case the field is parallel to the polarization vectors (which are perpendicular to the dust polarization vectors), and speculate that the magnetic field is bending the outflow (Figure 3). In the high mass protostar DR21(OH) Lai et al. also infer that the field traced by the linearly polarized CO emission is parallel to the field, by comparison with the polarized dust emission. Polarized CO emission is observed over a larger area than the dust, allowing the field morphology to be inferred over a similar area. Lai et al. deduce that the two dust continuum peaks (MM1 & MM2) are condensations within a magnetic flux tube. Applying the modified C-F method field strengths of $B_p \sim 1$ mG are inferred, about twice that found for B_{los} through CN Zeeman observations (Crutcher et al. 1999). Combining these results implies that the field is pointed toward us at an angle of ~30°to the line of sight.

3. Probing the Magnetic Field in 3D

For many years observational studies of magnetic fields in molecular clouds were restricted to probing the line-of-sight component via the Zeeman effect in thermal (non-maser) lines, or the plane of the sky component via dust polarization (and more recently linearly polarized spectral lines). A method to combine Zeeman observations with polarized background starlight was proposed by Myers & Goodman (1991; see also Goodman & Heiles 1994) to deduce the 3D field structure. However, this method has not been commonly used, perhaps a result of concerns about the usefulness of background polarized starlight in molecular clouds (depolarization; lack of stars), and the lack of Zeeman observations over the large angular sizes required at that time to obtain a sufficiently large number of stars for polarization studies. Recent theoretical simulations have shown that a modified C-F method can be used to infer the plane of the sky field strength under certain conditions (see Ostriker et al. 2001; Padoan et al. 2001; Heitsch et al. 2001a for specifics), and when applying this method to observational data care must be taken to ensure these conditions are met. If the field probed by the Zeeman effect and the dust polarization is believed to arise from a common region, then combining the Zeeman and C-F methods enables the full field strength and its angle to be determined. This has been attempted by Lai et al. (2003b) for DR21(OH) using CN 1-0 Zeeman data (Crutcher et al. 1999). Unfortunately the densities probed by the dust continuum ($> 10^5$ cm^{-3}) are not in general probed by OH, the molecular most used in Zeeman observations. Potential Zeeman sensitive molecules that probe these densities (CN, CCS, CCH, SO) are discussed later.

Another technique for probing the 3-D field structure in the weakly ionized regions of molecular clouds (i.e., dense cores) involves the use of Zeeman data, dust polarimetry, and measurements of the ratio of ion-to-neutral line widths (Houdé et al. 2002). The advantage of this technique over the simple one describe above is that all the quantities needed are measured directly by observations, unlike the modified C-F method. Houdé et al. used this method to infer the structure of the field in M17, and more recently Lai et al. (2003b) have used the technique to infer the field in DR21(OH) at high angular resolution, combining their BIMA data described above with new OVRO data. Although Lai et al. find that the angle of the field to our line of sight is unchanged from their earlier estimate, the field strength is significantly lower (0.4 mG cf. 1 mG), which they suggest is a result of overestimating the field strength using the modified C-F method, due to smoothing of the polarization dispersion in the BIMA data.

With the next generation of interferometers combining great improvements in sensitivity with high angular resolution (ALMA, SKA), it may be possible to use these techniques to determine the full field structure and strengths in a more representative sample of molecular clouds and cores.

4. Unanswered Questions & Future Directions

As stated at the beginning of this review there are two fundamental questions into which we would like to gain insight: (1) what is the dominant mechanism driving star formation, and (2) how important are magnetic fields at different stages in the star formation process?

The results discussed here unfortunately are inconclusive to answer (1). Most of the Zeeman observations and many of the polarization studies have been toward regions that are already forming stars, where the magnetic field should not be dominant. So it is no surprise that this is the result found through observations. In the few observations of starless cores, the observations again suggest the field is important though not dominant (Crutcher et al. 2004). However, the isolated starless cores L183 and L1544 show spectral signatures of inward motions (Lee et al. 2001), and so appear to be at an advanced stage of evolution just prior to collapse.

For core evolution most of the results suggest that by the time the protostellar stage is reached magnetic fields are not energetically dominant. But they are still important, as shown by the many observational examples of uniform and ordered polarization patterns, and in some cases the hourglass-like morphologies which might suggest core contraction due to ambipolar diffusion, as least during the inital stages of evolution toward forming a protostar.

At present the observations are insufficient to address (2). The observations of high mass regions suffer either from lack of resolution, even with interferometers, or don't sample the diffuse parts of molecular clouds which are more representative of the overall cloud than those regions that have obtained sufficient density to form stars and are therefore bright enough to be well detected by Zeeman or polarization studies. Studies of low mass regions suffer from similar problems, and in addition do not probe every evolutionary stage, from chemically young protostellar cores (Aikawa 2004), through to protoplanetary disks (Dutrey 2004; Wilner 2004).

New instruments will help us to obtain a little more knowledge on both these issues. In particular we highlight the importance of ALMA in dust polarization and linearly polarized emission line studies at (sub)mm wavelengths, and the SKA for Zeeman studies.

In order to make progress on question (1) we need Zeeman measurements throughout molecular clouds, which could be provided by OH Zeeman observations with the SKA of lines which are too weak to provide detections with existing telescopes. If the modified C-F method can be tested more thoroughly in simulations and if it is applied correctly to observational data, it may be a useful tool to provide information on the 3D field when used with Zeeman data. These observations will not be easy. The technique of Myers & Goodman (1991) to combine Zeeman and background polarized starlight observations to infer the 3D field structure should be re-examined as a tool to probe the lower density regions of molecular clouds (which contain the bulk of the material), particularly with today's 10-m class optical telescopes and infrared array cameras.

We would like to know the field strengths within dense protostellar cores before the onset of star formation. Observations using ALMA of CN 1-0 at 113.5 GHz, CCH at 85 GHz, and SO at 30 and 100 GHz, and the SKA of CCS at 11 and 22 GHz (Bel & Leroy 1989, 1998; Shinnaga & Yamamoto 2000), may provide these data, particular if the cores are carefully selected so that these molecules are not selectively depleted (e.g., L1521E). In such cores the method of Houdé et al. may provide information on the full 3D structure of the field. We would also like to know this information for protostellar cores at both the Class 0 and Class I phases, to examine the importance of the field during protostellar evolution.

In order to understand the high resolution observations of dust polarization, the observed depolarized at high intensities needs to be explained quantitatively.

Further, numerical simulations of turbulence dominant molecular clouds that include magnetic fields need to be able to resolve protostellar cores and their fields, and not just treat them as sink particles, for comparison with observations (Vázquez-Semadeni 2004).

The new generation of interferometers (CARMA, ALMA and SKA) will provide the sensitivity and resolution required to make progress on two questions where essentially no observational information exists on the magnetic field – how important are magnetic fields in protostellar disks (disk viscosity, angular momentum transport; Hartmann 1998), and what drives and collimates protostellar outflows and jets (X-wind – Shang 2004; Disk wind – Königl & Pudritz 2000). Zeeman observations of some or all of CN, CCH, CCS, and SO in thermal emission will be very important in the study of protostellar disks (Qi 2000; Dutrey 2004) and envelopes (van Dishoeck & Blake 1998; Aikawa 2004), in particular if the full field can be inferred by combining these data with linear polarization studies of dust and CO. Polarization observations at size scales of a few AU or better may help to decide which mechanism is responsible for launching and collimating protosteller jets. These observations will still be difficult even with ALMA et al.

So our final words are directly to those planning the construction of ALMA and the SKA:

- Please provide ALMA with good polarimeters for dust and spectral line polarization studies at submm wavelengths, and the capability for Zeeman observations down to 30 GHz.

- Please push the upper frequency of the SKA to at least 24 GHz, to allow for Zeeman observations of thermal CCS (22 GHz), of water masers (22 GHz), and non-Zeeman observations of the important inversion transitions of ammonia near 24 GHz. Please pay particular attention to the polarization characteristics of potential array designs.

THANKS!

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