Computational Star Formation
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Submillimeter Array Observations of Magnetic Fields in Star Forming Regions

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Abstract. There have been a number of theoretical and computational models which state that magnetic fields play an important role in the process of star formation. Competing theories instead postulate that it is turbulence which is dominant and magnetic fields are weak. The recent installation of a polarimetry system at the Submillimeter Array (SMA) has enabled us to conduct observations that could potentially distinguish between the two theories. Some of the nearby low mass star forming regions show hour-glass shaped magnetic field structures that are consistent with theoretical models in which the magnetic field plays a dominant role. However, there are other similar regions where no significant polarization is detected. Future polarimetry observations made by the Submillimeter Array should be able to increase the sample of observed regions. These measurements will allow us to address observationally the important question of the role of magnetic fields and/or turbulence in the process of star formation.

Keywords. stars: formation, ISM: magnetic fields,i ISM: dust, techniques: polarimetric

1. Introduction

In the "classical picture" of star formation, magnetic fields are believed to strongly influence star formation activity in molecular clouds. They provide support to a cloud against gravitational collapse and thus explain the low efficiency of the star formation process (See review by Mouschovias 2001). The process of ambipolar diffusion, in which magnetic flux is redistributed in the cloud, leads to the formation of a core that can no longer be magnetically supported and gravitational collapse sets in. In addition, the process of magnetic braking can help to remove angular momentum and slow down the rotation of the cloud as it collapses. In contrast, there have been a number of alternate theories which postulate that magnetic fields are relatively weak and supersonic magnetohydrodynamic turbulence is the dominant process (Mac Low & Klessen 2004). Turbulence controls the evolutions of clouds, and cores form at the intersection of supersonic turbulent flows. Only a fraction of such cores become supercritical and collapse begins to occur on a gravitational free-fall timescale.

It is therefore imperative to be able to measure the structure and morphology of the magnetic field in regions of active star formation in order to distinguish between the two competing theories. One of the ways of detecting magnetic fields is through observations of polarized dust emission from spinning dust grains (See review by Hildebrand 1988). In the presence of magnetic fields, spinning dust grains in the interstellar medium become aligned such that their short axis becomes parallel to the direction of the magnetic field. The exact nature of the alignment process is still being studied by a number of theorists

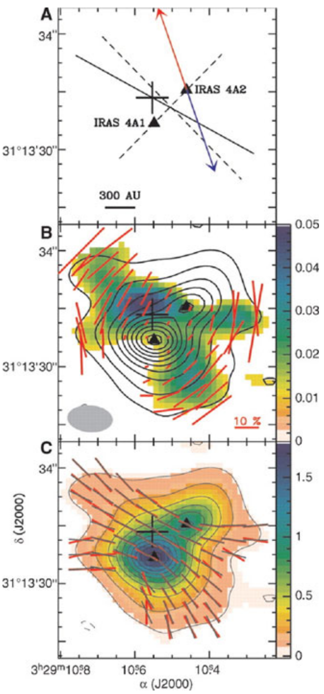

Figure 1. Polarization in NGC 1333 IRAS 4A: (A) Sketch of the axis directions: red/blue arrows show the direction of the redshifted/blueshifted lobes of the molecular outflow, solid lines show the main axis of the magnetic field, and dashed lines show the envelope axes. The solid triangles show the position of IRAS 4A1 and 4A2. The small cross shows the centre of the magnetic field symmetry. (B) Contour map of the 877 μm dust emission (Stokes I) superposed with the color image of the polarized flux intensity. Red vectors: Length is proportional to fractional polarization and the direction is position angle of linear polarization. The synthesized beam is shown in the bottom left corner. (C) Contour and image map of the dust emission. Red bars show the measured magnetic field vectors. Grey bars correspond to the best fit parabolic magnetic field model. Using the residuals from this fit, the strength of the magnetic field can be estimated with the Chandrasekhar-Fermi method.

(See review by Lazarian 2007). Previous observations of the polarization conducted at a number of observatories have either been hampered by sensitivity or angular resolution. The Submillimeter Array (SMA) is the ideal instrument to conduct such observations as it is not limited by the factors mentioned and is currently the only interferometer array that can do so.

2. Observations with the SMA

Figure 1 shows the first SMA observations at 345 GHz of the polarized dust continuum emission observations of a young stellar object (YSO) NGC 1333 IRAS 4A reported by Girart, Rao, & Marrone (2006). For the first time, it was shown that in a low-mass star forming region, the observed properties of the magnetic field are in agreement with the standard theoretical models of isolated star formation in magnetized molecular clouds: the magnetic field traces a clear "hour glass" morphology. On larger scales the polarization direction is quite uniform at a position angle of $\sim 145°$ and is in excellent agreement with earlier lower resolution observations. However, on small scales ($\sim$ 200 AU) the field is significantly distorted or "pinched" and the morphology resembles the "hour glass" shape that is predicted by theory. Using the intrinsic dispersion of the polarization angles (Chandrasekhar & Fermi 1953), it is possible to infer the strength of the magnetic field to be 4 mG. The analysis reveals that the magnetic field is substantially more important than turbulence in the evolution of the NGC 1333 IRAS4A circumbinary envelope. A similar magnetic field topology is also seen in IRAS 16293 which is another well studied region of low mass star formation in Ophiuchus (Rao *et al.* 2009).

In contrast to NGC 1333 IRAS 4A which is a low mass YSO, G31.41+0.31 is a region where high mass stars are forming. It harbors a massive ($\sim$ 500-1500 $M_\odot$) rotating hot molecular core. Embedded inside this core are young stellar objects which are in a very

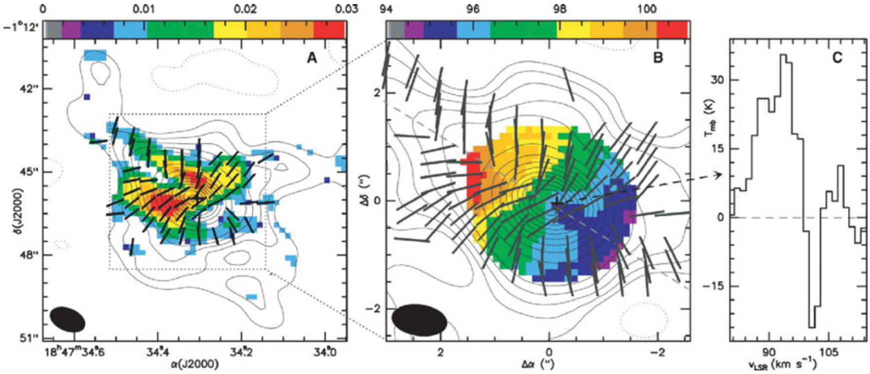

Figure 2. Polarization in G31.41: (A) Contour map of the 879 μm dust emission superposed on the color image of the polarized flux intensity. Black thick bars indicate the position angle of the magnetic field. The full width half maximum synthesized beam is $1.34'' \times 0.83''$ with a position angle of 67° (shown in the bottom left corner). (B) Contours of the 879 μm dust emission superposed on the color image of the flux weighted velocity map of the CH3OH 147-156 A. Black thick bars indicate the direction of the magnetic field. (C) Spectrum of the C34S 7-6 line at the position of the dust emission peak.

early stage of their evolution. The mass of the toroid containing the protostellar objects is much larger than the dynamical mass required for equilibrium, which suggests that the toroid may be gravitationally unstable and undergoing collapse. The dust continuum polarimetry observations (in addition to spectral line maps) carried out with the SMA in the compact and extended configuration at 345 GHz have enabled mapping of this massive hot core at angular resolution slightly below one arcsecond, tracing scales of several thousand AU (Girart *et al.* 2009). The maps (Figure 2) clearly show that the magnetic field lines threading the hot core are pinched along the major axis of the core, where the velocity gradient due to rotation is observed, acquiring a "hour glass" morphology. Furthermore, mapping the spectral line emission from the $C^{34}S$ molecule shows an inverse P-Cygni profile, indicative of infall motions. In addition, a comparison of the velocity gradient along the major axis for different methanol lines show a smaller rotation velocity in the more spatially compact lines (typically the higher excitation ones). This implies that the angular momentum is not conserved during the collapse process. The analysis of the SMA data show that the magnetic field dominates energetically (with respect to centrifugal and turbulence forces) the dynamics of the collapse, and that there is evidence of magnetic braking.

The SMA observations of the polarized emission can also be used to provide information on the nature and efficiency of the dust grain alignment mechanisms. Previous observations (Tamura *et al.*, 1999) and theoretical predictions (Cho & Lazarian 2007) have suggested that a polarization fraction of 2-3% should be commonly observed for protoplanetary disks around young stars. SMA observations of the disk around HD 163296 (Figure 3; Hughes *et al.* 2009), do not detect any polarized emission from either disk. The observations set the most stringent limits to date on the millimeter wavelength polarization from protoplanetary disks, and rule out the fiducial Cho & Lazarian (2007) model at the 10-sigma level. By comparing the SMA observations to the model predictions of Cho & Lazarian (2007), it is determined that the factors most likely contributing to the suppression of polarized emission relative the fiducial model are the roundness of large grains, inefficient alignment of grains with the magnetic field, and a random "tangled" component to the magnetic field lines.

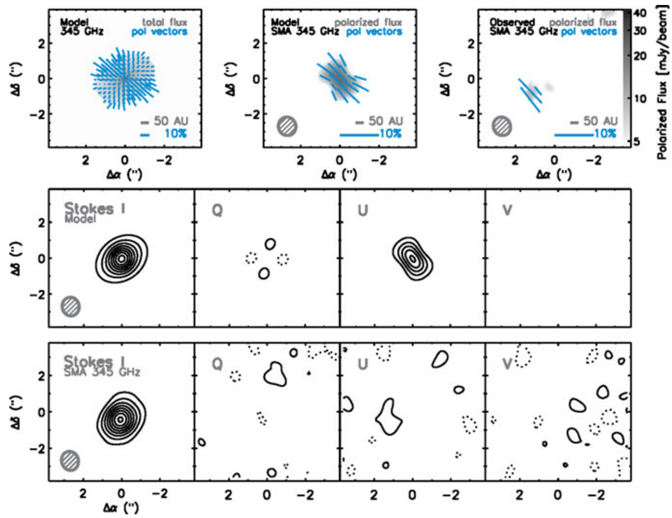

Figure 3. Comparison between the Cho *et al.*, (2007) model and the SMA 340 GHz observations of HD 163296. The top row shows the prediction for the model at full resolution (left), a simulated observation of the model with the SMA (center), and the 2008 SMA observations (right). The grayscale shows either the total flux (left) or the polarized flux (center, right), and the blue vectors indicate the percentage and direction of polarized flux at half-beam intervals. The center and bottom rows compare the model prediction (center) with the observed SMA data (bottom) in each of the four Stokes parameters (I, Q, U, V, from left to right).

3. Summary and Conclusions

These are a few of the results obtained at the SMA which have made a significant contribution towards understanding the nature of the star formation process. Polarimetric observations of a number of other active star forming regions also appears to indicate that the effects of magnetic fields are quite strong and possibly even dominate the star formation process in such regions. These observations are among the most challenging ones conducted at the SMA as they require high sensitivity as well as precise instrumental calibration. The future use of dual polarization receivers at 345 GHz will vastly improve the sensitivity and simplify the operation. This will enable us to make such observations towards an even larger statistical sample of YSOs enabling us to better understand the role of magnetic fields and turbulence in the star formation process.

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