FROM POLOIDAL TO TOROIDAL: DETECTION OF A WELL-ORDERED MAGNETIC FIELD IN THE HIGH-MASS PROTOCLUSTER G35.2—0.74 N

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ABSTRACT

We report the detection of an ordered magnetic field threading a cluster-forming clump in the molecular cloud G35.2—0.74 using Submillimeter Array observations of polarized dust emission. We resolve the morphology of the magnetic field in the plane of sky and detect a great turn of 90° in the field direction: over the northern part of the clump, where a velocity gradient is evident, the magnetic field is aligned along the long axis of the clump, whereas in the southern part, where the velocity structure is relatively uniform, the field is aligned perpendicular to the clump. Taking into account early single-disk data, we suggest that the clump forms as its parent cloud collapses more along the magnetic field. The northern part of the clump carries over angular momentum from the cloud, forming a fast rotating system, and the magnetic field is pulled into a toroidal configuration. In contrast, the southern part is not significantly rotating and retains a poloidal field. A statistical analysis of the observed polarization dispersion yields a field strength of \(\sim 1\) mG. Detailed calculations support our hypothesis of a rotationally twisted magnetic field in the northern part. The observations suggest that the magnetic field may play a critical role in the formation of the dense clump, while in its further dynamical evolution, rotation and turbulence can also be important. In addition, our observations provide evidence for a wide-angle outflow driven from a strongly rotating region whose magnetic field is largely toroidal.

Key words: ISM: magnetic fields – stars: early-type – stars: formation – techniques: interferometric – techniques: polarimetric

Online-only material: color figures

1. INTRODUCTION

The role of magnetic fields in the evolution of molecular clouds and the formation of stars has long been subject to great debate (see Crutcher 2012 for a review). In a classic model of low-mass star formation, molecular clouds are supported by magnetic fields and stay in subcritical states, evolving quasi-statically; ambipolar diffusion induces the formation of supercritical cores that dynamically collapse to form stars (Shu et al. 1987; Basu & Mouschovias 1994; Mouschovias et al. 2006). The other view is that molecular clouds are short lived, dynamically evolving, and producing stars rapidly (Elmegreen 2000; Hartmann et al. 2012), with magnetic fields being implicitly weak or not really appreciable in cloud evolution and star formation; Mac Low & Klessen (2004) further strongly argue that supersonic turbulence, instead of magnetic fields, supports molecular clouds and regulates star formation. On the other hand, our understanding of high-mass star formation is far less clear, but the competing views on the role of magnetic field/turbulence are equally, if not more strongly debated. Recent magnetohydrodynamic (MHD) simulations suggest that magnetic fields are dynamically important in high-mass star formation, in particular at suppressing complete fragmentation and creating bipolar outflows (Banerjee & Pudritz 2007; Peters et al. 2011; Hennebelle et al. 2011; Commerçon et al. 2011; Seifried et al. 2012; Myers et al. 2013).

The “magnetic support” model predicts a well-ordered or, in the extreme case, uniform magnetic field permeating a molecular cloud (Ostriker et al. 2001). Since there is an increased support against gravity in the direction perpendicular to the magnetic field compared with the direction parallel to it, the cloud contracts more along the field, forming flattened cores orthogonal to the mean direction of the field (Matsumoto & Tomisaka 2004; Tassis et al. 2009). In contrast, in the “weak field” or “turbulent support” model, the magnetic field is expected to show an irregular and even chaotic morphology due to overwhelming turbulent twisting (Ostriker et al. 2001; Padoan et al. 2001). Therefore, mapping the morphology of the magnetic field provides a straightforward method to distinguish between the two competing paradigms and provide insight into the possibility of a scenario where both magnetic fields and turbulence are important. Focusing on massive clumps or cores with a typical size scale of 0.1 pc and a distance of a few kiloparsecs, high angular resolution observations of polarized dust emission are needed to spatially resolve the magnetic field morphology. Submillimeter Array\(^{6}\) (SMA) observations have been playing a major role in recent studies of this kind, although the observations are still limited to a small number of case studies (e.g., Girart et al. 2009; Tang et al. 2013; Liu et al. 2013; Girart et al. 2013). Here, we present an SMA study of a massive cluster-forming clump that shows an elongated morphology projected on the plane of the sky and thus defines an axis ready to be compared with the direction of the magnetic field.

\(^{6}\) The SMA is a joint project between the Smithsonian Astrophysical Observatory and the Academia Sinica Institute of Astronomy and Astrophysics and is funded by the Smithsonian Institution and the Academia Sinica.
The targeted clump (hereafter G35.2N) lies in the northern part of G35.2−0.74, a molecular cloud first discovered by Brown et al. (1982) and located at a distance of 2.19 kpc (Zhang et al. 2009a). It is associated with the IRAS source 18566+0136, which has a total luminosity of $3 \times 10^{4} \, L_{\odot}$ (Dent et al. 1989; Sánchez-Monge et al. 2013). Early molecular line observations revealed a velocity gradient along the long axis of the clump, as well as a large-scale bipolar outflow approximately orthogonal to the clump elongation (Dent et al. 1985; Little et al. 1985; Brebner et al. 1987). G35.2N was thus interpreted as a rotating interstellar disk or toroid. More detailed studies of the molecular outflow were presented by Gibb et al. (2003) and Birks et al. (2006). Most recently, Zhang et al. (2013) presented SOFIA-FORCAST mid-infrared observations of G35.2N and modeled the object as a single high-mass protostar forming by an ordered and symmetric collapse of a massive core with a radius of 0.1 pc. However, both Atacama Large Millimeter/submillimeter Array (ALMA) cycle 0 observations (Sánchez-Monge et al. 2013) and the SMA data presented here reveal an apparently filamentary and highly fragmented structure for the dense gas on a 0.15 pc scale. We furthermore infer a well-ordered B field from sensitive observations of the polarized dust emission and find that the B-field morphology correlates with the dense gas kinematics.

2. OBSERVATIONS AND DATA REDUCTION

The observations were carried out with the SMA from 2010 to 2012, using three array configurations under excellent weather conditions. Detailed information on the observations, including the observing dates, array configurations, number of available antennas, atmospheric opacities at 225 GHz, and various calibrators, is presented in Table 1. For the Subcompact and Extended observations, the 345 GHz receiver was tuned to cover roughly 332–336 GHz in the lower sideband and 344–348 GHz in the upper sideband. For the Compact observations, the frequency setup covers about 333.5–337.5 GHz in the lower sideband and 345.5–349.5 GHz in the upper sideband. For all the observations, the correlator was configured to have a uniform spectral resolution of 812.5 kHz ($\sim 0.7 \, \text{km s}^{-1}$).

We performed basic data calibration, including bandpass, time-dependent gain, and flux calibration, with the IDL MIR package and output the data into MIRIAD for further processing. The intrinsic instrumental polarization (i.e., leakage) was removed to a 0.1% accuracy (Marrone & Rao 2008) with the MIRIAD task GPCAL. For each sideband, a pseudo-continuum dataset was created from spectral line-free channels using the MIRIAD task UVLIN. The calibrated visibilities were jointly imaged to make Stokes $I$, $Q$, and $U$ maps. We performed self-calibration with the continuum data in Stokes $I$ and applied the solutions to both continuum and spectral line data in Stokes $I$, $Q$, and $U$. Finally, the Stokes $I$, $Q$, and $U$ maps were combined to produce maps of the polarized emission intensity, the fractional polarization, and the polarization angle, using the MIRIAD task IMPOL. No significant polarization is detected in molecular line emission, so only Stokes $I$ maps are presented for spectral lines.

3. RESULTS

3.1. Dust Emission and the Magnetic Field

Figure 1 shows the total dust emission on a variety of size scales. In the James Clerk Maxwell Telescope7 (JCMT) SCUBA 850 $\mu$m map with a 15″ resolution (Figure 1(a)), the emission unveils a $\sim 0.5$ pc, slightly elongated clump, which shows hierarchical fragmentation in our SMA observations. In the SMA 880 $\mu$m map made by combining the Subcompact and Compact observations (Figure 1(b)), the inner clump splits into three cores, MM1–3, each with a diameter of order 0.05 pc. Convolving the SMA map to the SCUBA beam and comparing its peak flux ($\sim 6$ Jy) to that of the SCUBA map ($\sim 8.5$ Jy), the SMA observations recover approximately 70% of the total flux. Figure 1(c) shows the SMA map made from all the observations spread over five tracks (Table 1). With a uniform weighting of the data, we obtain an angular resolution of 1′′0 × 0′′6 and resolve each of the three cores into at least two condensations with diameters of 0.01–0.02 pc. These condensations are distributed approximately along the major axis of the clump, but in MM2, there are minor emission peaks to the west. MM1b approximately coincides with an unresolved radio source first detected at 8.5 GHz (Gibb et al. 2003). Sánchez-Monge et al. (2013) presented the ALMA 860 $\mu$m continuum map at a 0′′4 resolution. Our SMA map shown in Figure 1(c) is, in general, consistent with the ALMA observations.

To achieve the highest possible sensitivity, which is desirable for a polarization study, we jointly imaged all the SMA observations using natural weighting, which results in a rms noise level, $\sigma$, of 1.5 mJy beam$^{-1}$. Strong polarization of the dust emission (signal-to-noise ratios (S/N) greater than 3) is detected toward MM1, MM3, and part of MM2 (Figure 2(a)) and thus the inferred B field in the plane of the sky is well resolved (Figure 2(b)). We detect a clearly ordered B field threading the clump. Over the northern two cores MM1 and MM3, the B-field direction is overwhelmingly aligned with the long axis of the clump, whereas approaching the southern core MM2, the B-field

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Table 1

| Date of Observations | Configuration | Number of Antennas | t225 | Bandpass$^a$ Calibrator | Gain Calibrator | Flux Calibrator |
|----------------------|---------------|-------------------|------|-------------------------|----------------|-----------------|
| 2010 Oct 5           | Compact       | 7                 | 0.05 | 3C273                   | J1751+096      | Titan           |
| 2011 Jul 2           | Subcompact    | 7                 | 0.07 | 3C279                   | J1751+096      | Callisto        |
| 2011 Jul 21          | Extended      | 7                 | 0.05 | 3C279                   | J1751+096      | Callisto        |
| 2011 Jul 23          | Extended      | 8                 | 0.06 | 3C279                   | J1751+096      | Callisto        |
| 2012 Mar 28          | Extended      | 6                 | 0.07 | 3C279                   | J1751+096      | Titan           |

Note. $^a$ Also used for instrumental polarization (leakage) calibrations.

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7 The James Clerk Maxwell Telescope is operated by the Joint Astronomy Centre on behalf of the Science and Technology Facilities Council of the United Kingdom, the Netherlands Organisation for Scientific Research, and the National Research Council of Canada.
direction drastically changes by about 90° so that it is perpendicular to the clump elongation. Interestingly, early single-dish polarimetric observations with a 14″ beam revealed a mean direction at a position angle (PA) of 56° for the B field permeating the parent cloud of the clump (Vallée & Bastien 2000, also see Figure 2(b)). Therefore, over MM1 and MM3, the B field in the dense clump is approximately perpendicular to the mean direction of the large-scale B field, while toward MM2, the B field in the clump roughly follows that in the cloud. In addition, to the southwest of MM1 and to the east of MM2, there are B-field segments inclined to the direction of the cloud B field. Even for the northern part of the clump, the direction of the B field on the edges of the clump tends to deviate more from the clump major axis.

3.2. Molecular Line Emission

Our SMA observations cover a large number of spectral lines tracing molecular gas under a variety of physical conditions.

Figure 1. Total dust continuum emission, shown in both inverse gray scale and contours, at 850 μm observed with JCMT SCUBA and at 880 μm with the SMA. (a) The SCUBA map, with starting and spacing contour levels of 1 Jy beam$^{-1}$. (b) The SMA map made from the Subcompact and Compact data, with contour levels of 0.04 × (1, 2, 3, . . .)$^{1.5}$ Jy beam$^{-1}$. (c) The SMA map made from all the data available, with contour levels of 0.015 × (1, 2, 3, . . .)$^{1.5}$ Jy beam$^{-1}$. A plus sign marks the position of a weak radio continuum source (Gibb et al. 2003). Negative emission is invisible since the absolute levels are all below the lowest contour levels shown here. Hereafter, a filled ellipse in the lower right or left of a panel depicts the beam size at FWHM.

Figure 2. Panel (a): the total dust emission (Stokes I) shown in contours (solid for positive emission and dotted for negative emission) and the linearly polarized emission ($\sqrt{Q^2 + U^2 + \sigma^2}$) detected with $S/N \geq 3$ are shown in gray scale; the contour levels are ±0.03 × (1, 2, 3, . . .)$^{1.5}$ Jy beam$^{-1}$. The yellow segments indicate the directions of the linear polarization, with their lengths proportional to the fractional degree of the polarization; a scale bar in the lower right corresponds to a polarization degree of 5%.. The star symbols mark the peak positions of the six dust condensations. Panel (b): contours and star symbols are the same as in panel (a). The blue segments with an arbitrary length show the B-field directions, deduced by rotating the polarization directions by 90°. A large green bar indicates the direction of the B field obtained from early JCMT observations of the polarized dust emission at 760 μm (Vallée & Bastien 2000); a dashed circle marks the 14″ beam of the observations. The brown curves are drawn following a method proposed by Li et al. (2010) and outline the continuous variation in the direction of the B field at representative positions. (A color version of this figure is available in the online journal.)
No significant polarization is detected in these lines, but they allow a detailed investigation of gas kinematics.

### 3.2.1. Velocity Gradients in High-density Tracing Molecular Lines

We investigate the kinematics of the dense gas by examining the first moment (intensity-weighted velocity) maps (Figures 3(a)–(c)) and position–velocity (PV) diagrams (Figures 3(d)–(f)) of various molecular lines tracing high-density gas.

In Figure 3, the H$^{13}$CO$^+$ (4–3) emission traces the bulk dense gas of the clump seen in dust continuum. The most remarkable feature in the first moment map of the emission is a velocity shear lying between MM1 and MM2. From the PV diagram cut along the major axis of the clump (PA $-35^\circ$), MM2, which has a mean velocity close to the systemic velocity of the ambient cloud G35.2–0.74 (Roman-Duval et al. 2009), can be readily distinguished from the rest of the clump, MM1 and MM3, and a velocity gradient is clearly seen between the latter two cores’ locations. The CH$_3$OH (7$_1$–6$_1,6$)A emission preferentially traces the inner regions of the clump and reveals an overall velocity field consistent with that seen in H$^{13}$CO$^+$ (4–3). The HC$_3$N (38–37) line has an upper level energy of 324 K above the ground and probes the two condensations, MM1a and MM1b, embedded within MM1. There is a clear velocity gradient across...
the two condensations in the first moment map and $PV$ diagram of the HC$_3$N (38–37) emission. We also investigated our SMA (A color version of this figure is available in the online journal.)

The dense gas kinematics and the B-field morphology both suggest that the clump can be understood as a two-component structure: the northern part, which consists of MM1 and MM3, exhibits a velocity gradient of the order of 50 km s$^{-1}$ pc$^{-1}$ and the mean direction of the B field is aligned with the long axis of the clump; the southern part, i.e., MM2, does not show a clear velocity gradient and the B-field direction is perpendicular to the clump axis, such that it is aligned with the B field in the cloud.

3.2.2. Hot Molecular Cores and a Wide-angle Outflow

The two dust condensations embedded within MM1 (i.e., MM1a, b) are the brightest in the clump and show the richest molecular lines. MM1b coincides with (within 0.5′) a faint and spatially unresolved radio source detected at 8.5 GHz (Gibb et al. 2003). Following Qiu & Zhang (2009) and Qiu et al. (2011b), we perform a local thermodynamical equilibrium (LTE) fitting to the $K$ ladder of the CH$_3$CN (19–18) emission that is detected toward these two condensations. In Figure 4, the best-fit model agrees well with the observations and yields a temperature of 135 K, shown in a dashed curve. A very strong spectral line with a (sky) frequency of $\sim$349.07 GHz is CH$_3$OH (14$_{1,13}$–14$_{0,14}$) and is irrelevant to the fitting to the CH$_3$CN lines.

(A color version of this figure is available in the online journal.)

Figure 4. Solid histograms show the observed spectra of the CH$_3$CN (19–18) $K$ ladder, overlaid with the best-fit LTE model, which yields a gas temperature of 135 K, shown in a dashed curve. A very strong spectral line with a (sky) frequency of $\sim$349.07 GHz is CH$_3$OH (14$_{1,13}$–14$_{0,14}$) and is irrelevant to the fitting to the CH$_3$CN lines.

4. DISCUSSION

4.1. The B-field Strength and its Significance Compared with Turbulence and Gravity

We detect a structured B field threading the clump (Figure 2). The observed PA dispersion is attributed to both ordered and random perturbations to the B field and the latter is probably dominated by turbulence. However, dynamical processes related to cluster formation could perturb the B field in a manner rendering some disordered-to-random variations. We perform a statistical analysis of the observed PA dispersion to quantify the random perturbations (Hildebrand et al. 2009; Houde et al. 2009; Koch et al. 2010). Assuming the observed B field to be composed of a large-scale, ordered component, $B_0$, and a turbulent component, $B_t$, Houde et al. (2009) show that the dispersion function $1 - \langle \cos(\Delta \Phi(l)) \rangle$, which is measurable with a polarization map, can be approximately expressed as

$$1 - \langle \cos(\Delta \Phi(l)) \rangle \approx \frac{1}{N} \left( \frac{B_t^2}{B_0^2} \right) \times \left[ 1 - e^{-\delta^2/2(W^2+\delta^2)} \right] + a_2 l^2,$$

where $\Delta \Phi(l)$ is the difference in PA measured at two positions separated by a distance $l$ and $\langle \cdot \cdot \rangle$ denotes an average, $\delta$ is the turbulent correlation length, $W$ is the beam radius (i.e., the FWHM beam divided by $\sqrt{8 \ln 2}$), and $a_2$ is the slope of the second-order term. $N$ is the number of independent turbulent cells probed by observations and is defined by

$$N = \frac{(\delta^2 + 2W^2)\Delta'}{\sqrt{2\pi} \delta^3},$$

where $\Delta'$ is the effective depth of the cloud along the line of sight. Here, turbulence is implicitly adopted to be the only source of the
Figure 6. Panel (a): plus signs show the measured dispersion function, $1 - \langle \cos(\Delta \Omega(t)) \rangle$. For most data points, the error bars are too small to see (barely visible when $l > 9^\circ$). A solid curve shows the fitted function, $(1/N)\langle B^2_i \rangle / \langle B^2_0 \rangle \times [1 - e^{-l^2/(2\delta_l^2 + 2W^2)}] + a_i l^2$, for $l \lesssim 6^\circ$; a dashed curve shows the sum of the integrated turbulent contribution and the large-scale contribution, i.e., $(1/N)\langle B^2_i \rangle / \langle B^2_0 \rangle + a_i l^2$. Panel (b): the correlated component of the dispersion function; data points (shown in plus signs) are derived by subtracting the measured dispersion function from $(1/N)\langle B^2_i \rangle / \langle B^2_0 \rangle + a_i l^2$; the fitted $(1/N)\langle B^2_i \rangle / \langle B^2_0 \rangle e^{-l^2/(2\delta_l^2 + 2W^2)}$ is shown in a solid curve. A dashed curve shows the correlation solely due to the beam of the observations.

(A color version of this figure is available in the online journal.)

Chandrasekhar & Fermi (1953),

$$\left[\frac{\langle B_i^2 \rangle}{\langle B_0^2 \rangle}\right]^{1/2} = \frac{\delta \langle V_{\text{los}} \rangle}{V_\Lambda},$$

where $\delta V_{\text{los}}$ is the one-dimensional velocity dispersion and $V_\Lambda = B_0/\sqrt{4\pi \rho}$ is the Alfvén velocity at mass density $\rho$. Consequently, we can estimate the energy ratio of the turbulence to the ordered B field, $\beta_{\text{turb}} \sim 3(\langle B^2_i \rangle / \langle B^2_0 \rangle)$, to be 0.7–1.9. The ratio is somewhat overestimated considering that we are probing the B field in the plane of the sky and $B_i$ is not necessarily all ascribed to turbulence. Nevertheless, the statistical analysis suggests that the ordered B field and turbulence are energetically comparable.

The strength of the ordered B field can be derived following

$$B_0 = \sqrt{4\pi \rho \cdot \delta V_{\text{los}}} \left[\frac{\langle B_i^2 \rangle}{\langle B_0^2 \rangle}\right]^{-1/2}.$$

The H$^3$CO$^+$ (4–3) emission traces a structure similar to that seen in the dust emission and we estimate $\delta V_{\text{los}} \sim 1$ km s$^{-1}$ from the line-of-sight velocity dispersion of the H$^3$CO$^+$ line. To estimate $\rho$, we first compute the mass of the clump from its dust emission, which requires the information on the dust temperature and opacity. In our SMA observations, the clump consists of three cores, MM1–3, each of which harbors a couple of dust condensations. Toward MM2 and MM3, early NH$_3$ (1, 1) and (2, 2) observations deduced a rotational temperature of 20–25 K, corresponding to a kinetic temperature of 30–40 K (Little et al. 1985). Toward MM1, our LTE model of the CH$_3$CN (19–18) $K$ ladder gives a temperature of 135 K for the embedded HMCs, while recent high angular resolution NH$_3$ observations suggest a temperature $>50$ K (Codella et al. 2010). Thus, we adopt a gas temperature of 50–135 K for MM1. Assuming thermal equilibrium between gas and dust, the derived gas temperature approximates the dust temperature. The dust opacity index, $\beta$, is derived by comparing the dust emission fluxes at 880 $\mu$m and 1.3 mm (the latter is obtained from our new SMA observations). The dust opacity at 880 $\mu$m is then extrapolated from $10^\nu/1.2$ THz$^2$, where $\nu$ is frequency, following Hildebrand (1983). Assuming a canonical gas-to-dust mass ratio of 100, the masses of the three cores are then computed from their dust emission fluxes (Table 2). The total mass of the clump amounts to $\sim 150 M_\odot$ and results in an averaged column density of $\sim 3.7 \times 10^{25}$ cm$^{-2}$ over a measured area, $s$, of 200 arc sec$^2$ (0.015 pc$^2$), where the emission is detected with $S/N > 5$. If we adopt a volume of $4/3\pi s^3/\nu$, the averaged volume density is $\sim 1.0 \times 10^6$ cm$^{-3}$. We then obtain $B_0 \sim 1.4–0.9$ mG, again depending on $\Delta'$. Consequently, the mass-to-magnetic flux ratio, $M/\phi_B$, is 1.9–3.2 in units of the critical value, $1/(2\pi \sqrt{G})$, where $G$ is the gravitational constant (Nakano & Nakamura 1978), indicating that the clump is unstable against gravitational collapse and fragmentation. All the quantities derived from the statistical analysis of the PA dispersion are listed in Table 3.

It has been shown that a star-forming cloud generally collapses to a flattened or filamentary configuration to allow efficient fragmentation to follow (Larson 1985; Pon et al. 2011). The observations of the G35.2N clump are consistent with this theoretical prediction. To further understand the fragmentation property of the clump, it is instructive to compute the thermal Jeans mass, which is about 1.5 $M_\odot$ at a density of

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8 We exclude the southern part to constrain the PA in the range $[0^\circ, 90^\circ]$. 
1.0 \times 10^6 \, \text{cm}^{-3} \text{ and a temperature of 30 K. The analyses of} \text{ the gravitational instability of molecular gas sheets and filaments by \cite{Larson1985} are probably of more relevance to G35.2N.} \text{ Larson (1985) argued that rotation and magnetic field do not fundamentally change the characteristic mass, } M_c(M_\odot) = 2.4T^2/\mu, \text{ where } T = \text{the gas temperature and } \mu = \text{the surface density in } M_\odot \, \text{pc}^{-2}, \text{ of the fragments. For G35.2N, } M_c \approx 0.22 M_\odot. \text{ Even without taking into account the mass of the forming stars and the gas already dispersed by the wide-angle outflow, the clump mass is orders of magnitude greater than the Jeans mass or } M_c \text{ and is expected to fragment into hundreds of density enhancements if the dynamics is solely controlled by the gravity and thermal pressure. In Figure 1(c), there are only six prominent condensations detected at a spatial resolution (0.01 pc) finer than the Jeans length (0.04 pc). We also perform a multi-component Gaussian fitting to the dust emission using the MIRIAD task IMFIT and identify three new possible condensations, MM1c, MM2c, and MM2d (see Figure 7). Nevertheless, the total number of the condensations is far fewer than what is expected for thermal fragmentation. Such observational results have been seen in some other high-mass star-forming regions (\cite{Zhang2009b, Qiu2011b}) and strongly suggest that other mechanisms, e.g., turbulence, magnetic fields, and rotation, are playing important roles in the dynamical evolution of the clump. A highly turbulent core with a radius of 0.1 pc and a mass of 240 \, M_\odot, as described by \cite{Zhang2013} in applying the model of \cite{McKee2003} to G35.2N, is obviously inconsistent with the high angular resolution observations obtained here with the SMA and with ALMA (\cite{Sanchez-Monge2013}). Recent numerical simulations of the collapse and fragmentation of magnetized, massive star-forming cores show that cores with \( M/\phi_B \approx 2 \) form a single star rather than fragmenting into a small cluster (e.g., \cite{Commercon2011, Myers2013}). This is inconsistent with our observations; the measured \( M/\phi_B \) in G35.2N is \( \approx 2-3 \) and the clump is highly fragmented. We expect that both the \( B \) field and turbulence help to increase the effective Jeans mass or the characteristic mass of the fragments, but neither (or their combination) is sufficient to completely suppress fragmentation on \( \lesssim 0.1 \) pc scales.

4.2. Winding in the Deep —A Rotationally Distorted Magnetic Field?

4.2.1. A Schematic Picture

The sub-parsec clump in G35.2N has been interpreted as being a prototype of a massive interstellar disk or toroid, with the “disk” being nearly edge-on, having local standard of rest (LSR) velocities increasing from the northwest to the southeast (\cite{Dent1985, Little1985, Little1998, Brebner1987, Lopez-Sepulcre2009}). Our observations provide significant new insights into the dynamics of the clump. Going from the northern to the southern part of the clump, the B-field direction takes a 90° turn and is correlated with the velocity field revealed by the molecular lines tracing high-density gas (see Section 3.2.1). We also find that the B field in the southern part appears to be slightly pinched and can be fit with a set of parabolas (Figure 8), which provides marginal evidence for a magnetically regulated collapse of MM2 (e.g., \cite{Girart2006};
this part of the B field with a set of parabolas, $y = y_0 + g_x(x - x_0)^2$, measured directions of the B field in the southern part of the clump. We fit and squares are the same as those in Figure 7. The red segments show the mass of Gonçalves et al. 2008). In Figure 7, the dust condensations in the Note. a Except for $(\text{mpc})$ (mG) (1 $\circ$) (18 h 58 m 13.5 s $'$) (13 $'$ $''$). The red illustrate the blueshifted and redshifted lobes of a bipolar outflow. The solid and dotted lines show the magnetic field inside the clump (observed with the SMA) and that outside the clump (inferred from early JCMT observations), respectively. The cartoon is a schematic only and is not to scale in terms of the observed sizes of the various structures. (A color version of this figure is available in the online journal.)

Figure 8. Contours are the same as those in Figure 2; the symbols of stars and squares are the same as those in Figure 7. The red segments show the measured directions of the B field. We fit this part of the B field with a set of parabolas, $y = y_0 + g_x(x - x_0)^2$, following Girart et al. (2006) and Rao et al. (2009), and the best-fit model yields $C = 0.053$, the center of symmetry, $(x_0, y_0)$, located at (RA, decl.,) $= (18^h 58^m 13.1^s, +01^d 40^m 31.6^s)$ (denoted as a plus sign), and a P.A. of $- 51^\circ$ for the $y$-axis of the parabola. The dashed curves show a representative set of the fitted parabola. The blue segments depict the tangential directions of the fitted parabola at the positions where the B-field directions are measured.

(A color version of this figure is available in the online journal.)

Figure 9. Schematic view of our interpretation of the kinematics and magnetic fields in G35.2N. A filamentary structure in dark gray depicts the clump observed with the SMA and the six black dots indicate the deeply embedded dust condensations (see Figure 1(c)). The northern part of the clump is suggested to be rotating, as denoted by the curved arrows, whose colors represent the sense of the rotation. A large ellipse filled with light gray shows the parent cloud observable with the JCMT/SCUBA. Two parabolic structures in light blue and red illustrate the blueshifted and redshifted lobes of a bipolar outflow. The solid and dotted lines show the magnetic field inside the clump (observed with the SMA) and that outside the clump (inferred from early JCMT observations), respectively. The cartoon is a schematic only and is not to scale in terms of the observed sizes of the various structures. (A color version of this figure is available in the online journal.)

Table 3 Results from the Statistical Analysis of the PA Dispersion

| $\delta$ (mpc) | $N$ | $(B^2_f)/(B^2_0)$ | $\beta_{\text{ turb}}$ | $B_0$ (mG) | $M/\phi_B$ (1/2$\pi$ $\sqrt{G}$) |
|---------------|-----|-------------------|----------------------|------------|-------------------------------|
| 15.4          | 3.0–8.4 | 0.23–0.64 | 0.7–1.9 | 1.4–0.9 | 19.3–3.2 |

Note. a Except for $\delta$, all of the derived parameters depend on the effective depth, $\Delta' \sim 8''$–22''.

Gonçalves et al. 2008). In Figure 7, the dust condensations in the northern part are distributed approximately along the major axis of the clump, while those in the southern part have a Trapezium-like distribution. All this suggests that the clump is composed of two dynamically different components rather than coherently rotating as a whole.

One interpretation of the observed velocity gradient in the northern part is that it arises from the rotation of the dense gas. Considering the orientation of the B field in the cloud revealed by the single-dish observations (see Figure 2(b)), we speculate that the dense clump forms as the cloud collapses more along the direction of the large-scale B field. In this dynamical process, the dense gas breaks into two parts. The northern part carries over most of the angular momentum that is not dissipated and forms a fast rotating system. The system could be a rotating toroid embedded with multiple fragments. Or it is a hierarchical structure consisting of two cores (MM1 and MM3) in orbital motion and each core furthermore fragments and collapses into a binary or multiple star. In the latter case, the projected separation of $\sim 0.05$ pc and the line-of-sight velocity difference of $\sim 2.5$ km s$^{-1}$ between MM1 and MM3 yield a dynamical mass of $\gtrsim 73 M_\odot$, which is comparable with the combined mass of the two cores (Table 2). The southern part, however, does not participate in the rotating motion and is expected to have a mean velocity similar to that of the parent cloud. This hypothesis is indeed supported by the large-scale kinematics seen in $^{13}$CO (1$–0$) observations obtained from the Galactic Ring Survey, from which an LSR velocity of 35.2 km s$^{-1}$ is derived for the ambient cloud of G35.2N (Jackson et al. 2006; Roman-Duval et al. 2009, also see Figure 3). Also, one may expect that the angular momentum in the northern part has a significant influence on the fragmentation, causing the resulted fragments to be distributed within the rotational plane. The observed morphology of the B field in the clump can be naturally incorporated into the above scenario. Figure 9 provides an overall picture of our interpretations of the B-field structure: in the northern part, the B field is pulled by the rotation into a toroidal configuration, whereas in the southern part, the B field is only gently squeezed by the collapse and remains in a poloidal configuration (aligned with the B field in the cloud).

4.2.2. Quantitative Comparisons

We quantitatively investigate the feasibility of our interpretation of a rotationally distorted B field in the northern part of the clump. According to Matsumoto et al. (2006), a $90^\circ$ misalignment between the axis of an outflow and the mean direction of an ordered B field may occur if the rotational energy is at least comparable to the magnetic energy (also see Rao et al. 2009). Assuming the measured velocity gradient, $\Delta v/L$, in the northern part of G35.2N is arising from a disk-like structure with a diameter $L$, the rotational energy amounts to $1/2(M L^2/8)(\Delta v/L)^2$, where
$M$ is the mass of the rotating structure. The averaged ratio of the rotational energy to the magnetic energy, $\beta_{\text{rot}} = (\Delta u^2) / (8V_k^2)$, is found to be 0.5–1.3 for an end-to-end velocity difference of ~4 km s$^{-1}$ and $B_0 \sim 1.4$–0.9 mG. Hence, the rotational energy does appear to be comparable to the magnetic energy.

Alternatively, if a B field is wound by rotation into an overwhelmingly toroidal configuration, the centrifugal force is presumably overwhelming the magnetic force. More quantitatively, Machida et al. (2005) found that whether the centrifugal force or the magnetic force regulates the evolution of a collapsing core can be evaluated by the ratio of the angular velocity to the magnetic field strength, $\omega / B$. If this ratio exceeds a critical value, $0.39 \sqrt{G/c}$, where $c_i$ is the sound speed, the centrifugal force dominates the dynamics. For the G35.2N clump, $\omega \sim 5.1 \times 10^{-5}$ yr$^{-1}$ and $c_i \sim 0.33$ km s$^{-1}$ at 30 K, leading to $\omega / B \sim (3.6-5.7) \times 10^{-8}$ yr$^{-1}$ $\mu$G$^{-1}$, which is on the same order of but lower than the critical value of $9.7 \times 10^{-8}$ yr$^{-1}$ $\mu$G$^{-1}$. We stress that both $\omega$ and $c_i$ are averaged over the entire clump. Toward the inner part of the clump, $\omega$ increases since the cores appear to rotate faster and $c_i$ also increases since the gas temperature is higher. Thus, the measured $\omega / B$ would be greater than the critical value. For example, considering the dense gas in MM1, $\omega$ measures $\sim 1.5 \times 10^{-4}$ yr$^{-1}$ (Figure 3(f)) and $c_i$ reaches 0.71 km s$^{-1}$; the measured $\omega / B$ is more than two times greater than the critical value, confirming that the centrifugal force is dominating over the magnetic force.

The above calculations show that, energy wise, the B field is likely to be significantly distorted by the rotation. However, is there sufficient time for a toroidal B field to develop? The rotation period, $2\pi L / \Delta u$, is estimated to be $1.2 \times 10^5$ yr. The dense clump with an average density of $1.0 \times 10^6$ cm$^{-3}$ presumably formed from a cloud with a lower density ($\lesssim 10^2$ cm$^{-3}$), which has a free-fall time $> 10^7$ yr. In addition, with the detection of HMCs and a radio source in MM1, it is reasonable to expect that the clump has a dynamical age of order $10^5$ yr (e.g., Charnley 1997). Therefore, it is likely that the rotation has proceeded for a few periods and significantly distorted the B field into a predominantly toroidal configuration.

Finally, another piece of evidence supporting the presence of a toroidal B field in the clump comes from polarization observations (0′/2 resolution) of OH maser emission: Hutawarakorn & Cohen (1999) detected a few Zeeman pairs within 0′.5 of MM1b and found that the direction of the B field along the line of sight reverses from the southeast to the northwest of MM1b and the direction reversal was interpreted as being due to a toroidal B field.

4.2.3. Connecting the B Field to the Outflow

Both well-collimated and wide-angle outflows have been seen in high-mass star-forming regions (e.g., Qi et al. 2008, 2009, 2011a, 2012; Qi & Zhang 2009). Here in G35.2N, the CO (7−6) observations reveal a parsec-sized, wide-angle outflow (Figure 5; also see Figure 9). The outflow appears to originate from one of the two HMCs (MM1a or MM1b; see Section 3.2.2), which must have been undergoing collapse and spun up to form a rotating disk at the center. Indeed, there is evidence for the presence of a rotating disk in MM1b from ALMA observations (Sánchez-Monge et al. 2013), although it has yet to be confirmed whether the outflow is driven from MM1b. In line with our above interpretations, the ambient B field of the inner ~0.1 pc part of the outflow is dominated by a toroidal component and that component could be further traced down to a 0.01 pc scale taking into account previous OH maser observations (Hutawarakorn & Cohen 1999). Thus, the wide-angle outflow is most likely associated with a strong toroidal B field. How is this outflow driven?

Bipolar outflows in protostars or young stars are believed to be magnetically driven. In the most quoted magneto-centrifugal wind theory, the outflowing gas is centrifugally ejected, either from the inner edge of an accretion disk or over a wide range of disk radii, along open poloidal field lines (e.g., Shu et al. 1994; Shang et al. 2006; Pudritz et al. 2007; Fendt 2009). On the other hand, the magnetic tower model suggests that an outflow is accelerated by the magnetic pressure gradient of a wound-up volume of a toroidal B field (Uchida & Shibata 1985; Lynden-Bell 1996, 2003). Many MHD simulations of collapsing magnetized cores have shown that a bipolar outflow is launched from a strongly rotating region when a predominantly toroidal B field has been built up by the collapse spin-up process (e.g., Tomisaka 1998; Matsumoto & Tomisaka 2004; Banerjee & Pudritz 2006, 2007; Seifried et al. 2012). The observations of G35.2N are apparently consistent with such a scenario. Furthermore, numerical simulations often found two-component outflows: a larger, low-velocity, and less collimated outflow emerging earlier than an inner, faster, and jet-like outflow (e.g., Tomisaka 2002; Banerjee & Pudritz 2006; Machida et al. 2008; Seifried et al. 2012; Tomida et al. 2013). While some claim that the former is a magnetic tower flow and the latter is launched by the magneto-centrifugal force (Banerjee & Pudritz 2006, 2007), others argue for the opposite view (Machida et al. 2008; Tomida et al. 2013). The situation can be even more complicated considering the possible dependence of the outflow morphology on the B-field strength (e.g., Hennebelle & Fromang 2008; Seifried et al. 2012; Bate et al. 2013). In addition, radiation pressure could be important in widening massive outflows (Vaidya et al. 2011). Thus, we are not able to infer the driving mechanism of the G35.2N outflow solely based on its morphology. Regarding the B-field morphology, existing observations suggest a strong toroidal component in the inner part of the outflow, but a poloidal component certainly exists. To determine whether a magnetic tower or the centrifugal force dominates the acceleration of the outflowing gas, one may need a complete knowledge of the three-dimensional B field and velocity structures (Seifried et al. 2012). Since we are only probing the B field projected on the plane of the sky and the estimate of the B-field strength is indirect, it is not possible to compare the toroidal and poloidal components in detail. Hence, whether or to what extent a magnetic tower plays a role in accelerating the outflow remains open. However, if the growing tower is important, the central collapse-spin up process significantly helps to create at least part of the observed toroidal B field.

4.3. Infall Along a Magnetized Cylinder?

Provided the remarkable filamentary morphology of the clump seen in Figure 1(c), it is likely that we are observing a dense gas cylinder. A gas cylinder may fragment along its major axis due to the “sausage” or “varicose” instability and the resulted fragments will have a characteristic spacing (e.g., Jackson et al. 2010). In Figure 7(a), the dust condensations in the northern part are nearly equally spaced, in qualitative agreement with the fragmentation of a cylinder. Since a cylinder/filament is not expected to be rotating too fast about its minor axis, the observed velocity gradient (~50 km s$^{-1}$ pc$^{-1}$) is most likely

\footnote{Some large and extensively studied filaments are found to exhibit velocity gradients of only ~0.1–1 km s$^{-1}$ pc$^{-1}$ along their major axes.}
arising from infall motion along the cylinder axis rather than from rotation. From Figure 3(d), the infall velocity is \(\sim 2\sin i\) \(\text{km s}^{-1}\), where \(i\) is the inclination angle of the cylinder with respect to the plane of the sky. For a cylinder with a mass of \(100 M_\odot\) (roughly the gas mass of the northern clump plus the mass of the forming stars) and a length of 0.1 pc, the line-of-sight component of the free-fall velocity reaches \(\sim 4(\cos)^{1/2}\sin i\) \(\text{km s}^{-1}\), which is not incompatible (e.g., for \(i \approx 54^\circ\)) with the observed velocity gradient.

However, in the SCUBA map (Figure 1(a)), the clump is much less elongated and, on a larger scale, we do not detect any filamentary structure where the cylinder is embedded. Furthermore, self-gravitating cylinders have a critical linear mass density, \(2v^2/G\), where \(v\) is the sound speed, which in the case of thermal support (Stodólkiewicz 1963; Ostriker 1964) or the turbulent velocity dispersion \(\delta V_{\text{los}}\) in the case of turbulent support (Fiege & Pudritz 2000). Above the critical value, the cylinder would radially collapse into a line. The B field can be largely aligned with the long axis of the cylinder, the interpretation of a rotating system (Section 4.2) for the northern part of the clump appears more robust than that of a collapsing cylinder.

5. CONCLUSIONS

With the sensitive and high angular resolution observations made with the SMA, we detect a well-ordered B field threading G35.2N, which is an apparently filamentary, massive, and cluster-forming clump. Based on a statistical analysis of the observed polarization dispersion, we derive a B-field strength of \(\sim 1\) mG, a turbulent-to-magnetic energy ratio of the order of unity, and a mass-to-magnetic flux ratio of \(\sim 2\)–3 times the critical value.

The B-field morphology is found to vary depending on the kinematics revealed by molecular lines tracing high-density gas. In the northern part of the clump, which exhibits a velocity gradient, the B field is largely inclined to the line of sight (i.e., \(i > 60^\circ\)), the linear mass density seems to be too high to allow a stable cylinder to exist. Also, the southern part of the clump, which appears very different from the northern part in the B field, kinematics, and fragmentation properties, cannot be easily incorporated into a unified picture of a cylinder. Considering all these difficulties in understanding the observed clump as a cylinder, the interpretation of a rotating system (Section 4.2) for the northern part of the clump appears more robust than that of a collapsing cylinder.

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