MAGNETIC FIELD STRUCTURE IN THE FLATTENED ENVELOPE AND JET IN THE YOUNG PROTOSTELLAR SYSTEM HH 211

CHIN-FEI LEE1, RAMPRASAD RAO1, TAO-CHUNG CHING2, SHIH-PING LAI2,
NAOMI HIRANO1, PAUL T. P. HO1,3, AND HSJANG-CHIH HWANG1
1 Academia Sinica Institute of Astronomy and Astrophysics, P.O. Box 23-141, Taipei 106, Taiwan; clee@asiaa.sinica.edu.tw
2 Institute of Astronomy and Department of Physics, National Tsing Hua University, Hsinchu 30013, Taiwan
3 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

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ABSTRACT

HH 211 is a young Class 0 protostellar system with a flattened envelope, a possible rotating disk, and a collimated jet. We have mapped it with the Submillimeter Array in the 341.6 GHz continuum and SiO $J = 8–7$ at $\sim$0.6′ resolution. The continuum traces the thermal dust emission in the flattened envelope and the possible disk. Linear polarization is detected in the continuum in the flattened envelope. The field lines implied from the polarization have different orientations, but they are not incompatible with current gravitational collapse models, which predict a different orientation depending on the region/distance. Also, we might have detected for the first time polarized SiO line emission in the jet due to the Goldreich–Kylafis effect. Observations at higher sensitivity are needed to determine the field morphology in the jet.

Key words: ISM: individual objects (HH 211) – ISM: magnetic fields – polarization – stars: formation

1. INTRODUCTION

The magnetic field has important effects on low-mass star formation. It can launch a collimated jet but may suppress the formation of a rotationally supported (accretion) disk (RSD) in the early phase of star formation. In current theory, gravitational collapse of a rotating magnetized cloud core produces a flattened envelope and an hourglass field morphology around a central source (i.e., protostar; see, e.g., Allen et al. 2003). The flattened envelope is not rotationally supported and is thus called a pseudodisk. In the flattened envelope, the rotation velocity increases toward the center, generating a toroidal field in the inner part (Allen et al. 2003; Kataoka et al. 2012). However, the pinched geometry of the magnetic field in the flattened envelope generates a magnetic braking, suppressing the formation of an RSD around the center (Allen et al. 2003). One possible solution is a misalignment between the rotation axis and magnetic field axis (Joos et al. 2012; Li et al. 2013).

Observations of linearly polarized thermal dust emission toward low-mass Class 0 systems have revealed magnetic field morphologies of the envelope in support of the above theoretical picture. They have revealed an hourglass field morphology in, e.g., NGC 1333, IRAS 4A (Girart et al. 2006), and L 1157 (Stephens et al. 2013). They have also showed a tentative detection of toroidal fields near the center in, e.g., NGC 1333, IRAS 4A (Crutcher 2012), and IRAS 16293-2422 B (Rao et al. 2014). Moreover, a misalignment between the rotation axis and magnetic field axis could be common, as suggested in Hull et al. (2013). However, further observations are still needed to confirm the field morphology near the center and the misalignment.

On the other hand, the field morphology in the protostellar jet is poorly determined due to a lack of polarization detection. In current jet-launching models (Shu et al. 2000; Pudritz et al. 2007), a poloidal field is needed to launch the jet and a toroidal field is needed to collimate the jet. Therefore, the jet is expected to be magnetized with a helical field. For high-mass systems, the jet can emit synchrotron radiation, allowing us to map the field morphology with polarization observations in the synchrotron continuum (Carrasco-González et al. 2010). For low-mass systems, the jet can emit molecular line emission (Lee et al. 2007; Hirano et al. 2010). Line polarization has been detected in molecular outflows in low-mass systems, e.g., NGC 1333, IRAS 4A (Girart et al. 1999), and high-mass systems, e.g., DR 21 (Lai et al. 2003). It is attributed to the Goldreich–Kylafis (GK) effect (Goldreich & Kylafis 1981, 1982), and thus can be used to infer the field morphology in the molecular outflows. It can also be used to infer the field morphology in the jet.

HH 211 is a nearby (280 pc) low-mass system, in which a flattened envelope has been detected, an RSD has been claimed, and a collimated jet has been detected in SiO and CO down to the launching point inside an outflow cavity (Gueth & Guilloteau 1999; Lee et al. hereafter Lee et al. 2009). It is young in the Class 0 phase, with significant material still in the flattened envelope and a mass of only $\sim$0.06 $M_\odot$ for the central source. The jet is almost in the plane of the sky and the flattened envelope is almost edge-on, providing the best view of the fields. Here, we report detections of thermal dust polarization in the flattened envelope and line polarization in the jet, and discuss possible field morphologies in this system.

2. OBSERVATIONS

Polarization observations toward HH 211 were carried out with the Submillimeter Array4 (SMA; Ho et al. 2004) on 2013 November 28 in the extended configuration, using a dual-receiver mode with the 345 GHz and 400 GHz receivers. SiO ($J = 8–7$), CO ($J = 3–2$), and SO ($N J = 8_g–7_g$) lines were observed simultaneously with the continuum. Here, we only present the results in the continuum and SiO that show polarization detection. The receivers have two sidebands, lower and upper, covering the frequency range from 335.6 to 337.6 GHz and from 345.6 to 347.6 GHz, respectively. Combining the line-free portions of the two sidebands results in a total bandwidth of $\sim$3.7 GHz centered at $\sim$341.6 GHz for the

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leakages were found to be up to \(\sim 1.2\) mJy beam\(^{-1}\). The peak has a flux density of 112 mJy beam\(^{-1}\). The cross marks the source position. The blue and red arrows show the approaching and receding sides of the mean jet axis, respectively. In (a), the grayscale image shows the polarization intensity greater than 2\(\sigma\) detection, where the rms noise level \(\sigma = 1.15\) mJy beam\(^{-1}\). Line segments show the polarization vectors for the detection with 2\(\sigma\) to 3.5\(\sigma\) (orange for 2\(\sigma\)–2.5\(\sigma\), green for 2.5\(\sigma\)–3\(\sigma\), and red for 3\(\sigma\)–3.5\(\sigma\)). The polarization degree is indicated by the length of the vector. In (b), line segments show the magnetic field orientations. (c) shows the model density (white contours and color image) and field (red lines) morphology adopted from Kataoka et al. (2012), with the field axis (black lines) aligned with the jet axis of HH 211.

3. FLATTENED ENVELOPE

At 341.6 GHz, the continuum map shows a flattened structure within a radius of \(\sim 1''\) of the central source, roughly perpendicular to the jet axis (see Figure 1). The source is assumed to be at the peak position of the continuum, which is \(\alpha(2000) = 03^h 43^m 56^s 806, \delta(2000) = 32^\circ 00' 50.21''\), consistent with the position found at higher resolution (Lee et al. 2009). The jet is known to be bent and wiggling, with a mean axis at a P.A. of 114\(^\circ\) \pm 4\(^\circ\) (Gueth & Guilloteau 1999; Lee et al. 2007, 2009). The continuum has a total flux density of 220 \(\pm\) 30 mJy, consistent with the value found before. The center is unresolved, with a peak flux density of 112 mJy beam\(^{-1}\). A fit to the visibility amplitude versus \(uv\)-distance plot of the continuum requires two circular Gaussian components: an extended component with a size of \(\sim 1.8''\) and a compact component with a size of \(\sim 0.3''\). Thus, as discussed before, the continuum traces the thermal dust emission from a flattened envelope and a possible compact disk around the source (Lee et al. 2007, 2009). In Lee et al. (2009), a faint secondary source was detected at \(\sim 0.3''\) to the southwest of the central source at higher resolution. However, this source cannot be resolved here. The envelope is slightly asymmetric, extending further to the southwest than to the northeast (probably partly because of the secondary source) and further to the southeast than to the northwest.

3.1. Dust Polarization and Field Morphology

Linear polarization is detected in the thermal dust emission in the southeast, northeast, southwest, and northwest parts of the envelope, as shown by the polarization intensity map and vectors in Figure 1(a). The angles of the polarization vectors have an uncertainty of \(\sim 1''\). The degree of polarization reaches \(\sim 30%\) at the edges of the envelope, as found in other systems, e.g., NGC 1333 IRAS 4A (Girart et al. 2006). In the southeast part, the detection of the polarized emission has a peak of more than 3\(\sigma\) and is thus real. In other parts, the detections are 2\(\sigma\) to 3\(\sigma\) and thus should be considered tentative.

Figure 1(b) shows the magnetic field lines in the envelope obtained by rotating the polarization vectors by 90\(^\circ\). The field morphology is complicated because the field lines have different orientations in different regions. Along the major axis, the southwest field lines are roughly aligned with the jet axis slightly pinched toward the source. However, the northeast field lines, which are closer to the central source than the southwest field lines, are almost perpendicular to the jet axis. Along the minor axis, the northwest field lines appear to be roughly perpendicular to the jet axis. However, the southeast field lines, which are farther away from the central source than the northwest field lines, appear to be roughly aligned with the jet axis.

3.2. Comparison and Discussion

As mentioned earlier, current polarization observations support a gravitational collapse model of a rotating magnetized cloud core for low-mass star formation. For the first comparison, we compare to a simple version of such a model, in which the field lines are initially poloidal with the field axis aligned with the rotation axis. Because of the gravitational collapse, the field lines are pinched toward the source, forming an hourglass...
field morphology. Moreover, toroidal fields are generated by rotation in the flattened envelope near the source around the rotation axis. Figure 1(c) shows the three-dimensional view toward the inner part of such a model from Kataoka et al. (2012), where the toroidal field lines have formed. The model has a spatial scale about four times larger because it is 5–10 times older than HH 211, and is thus only used as an illustration of the complex structure of the magnetic field in the envelope. The model has an edge-on view, appropriate for HH 211. It is rotated with the field axis (black lines) aligned with the jet axis in HH 211. In addition, it has the same rotation sense as observed in HH 211, with the blueshifted part in the southwest and the redshifted part in the northeast (Lee et al. 2009).

The observed field morphology is complicated, but may not be incompatible with the model, as it predicts a different orientation depending on the region/distance. The northwest field lines can trace the toroidal fields in the flattened envelope generated by the rotation. The southeast field lines are farther away from the center and thus can trace the fields at the outer edge of the flattened envelope, where the fields are still mainly poloidal. The southwest field lines are slightly pinched and thus can trace the hourglass field lines dragged in by the gravitational collapse. The northeast field lines are located closer to the source, where the hourglass field lines are expected to be dragged in more by the gravitational collapse and thus bent to be roughly perpendicular to the jet axis (see also Figure 4(a) in Allen et al. 2003). Note that it is also possible that the field lines there trace the toroidal fields generated by the rotation, as claimed in the case of NGC 1333 IRAS 4A where field lines were also detected perpendicular to the jet axis (Crutcher 2012). In addition, the northeast/southwest asymmetry could also be partly due to the presence of a secondary source. The polarization is not detected in all parts of the envelope, probably because of depolarization due to the complicated field morphology and our insufficient angular resolution (Kataoka et al. 2012). Further observations at higher sensitivity and resolution are needed to confirm the different field orientations in different regions.

Hourglass field morphologies have been seen in other Class 0 systems, e.g., NGC 1333 IRAS 4A (a binary system) at $\pm 400$ AU resolution (Girart et al. 2006) and L 1157 at 300–525 AU resolution (Stephens et al. 2013). At higher, $\pm 180$ AU, resolution, toroidal field lines have also been detected tentatively in NGC 1333 IRAS 4A within 300 AU of the center (Crutcher 2012). In HH 211, a partial hourglass field morphology has also been seen at $\pm 1000$ AU resolution, with a pinched field morphology in the southwest (Hull et al. 2014). Here, at higher, $\pm 170$ AU, resolution, we may have detected not only the southwest hourglass field morphology farther in, but also the toroidal field lines in the flattened envelope within 300 AU of the center. Thus, higher resolution observations are needed to reveal the toroidal fields, likely because the rotation dominates only in the very inner region in the Class 0 phase.

In current theory, the pinched geometry of the magnetic field in the flattened envelope can produce magnetic braking, preventing an RSD from being formed at the center (Allen et al. 2003). However, such an RSD must have formed in order to launch the jet, as claimed in Lee et al. (2009). It has been argued that a magnetic field–rotation misalignment on a larger size scale could help the formation of the disk (Joos et al. 2012; Li et al. 2013). In a larger size cloud scale (arcminute scale; Matthews et al. 2009), the magnetic field lines are found to be roughly north–south oriented, neither aligned with nor perpendicular to the jet axis. However, the rotation axis on this scale is found to be roughly aligned with the jet axis (Lee et al. 2009; Tanner & Arce 2011). Thus, there is a misalignment of $\sim 30^\circ$ between the large-scale field axis and the rotation axis, and it may help the disk formation.

4. JET

Figure 2 shows the blueshifted (black contours) and redshifted (gray contours) components of the jet in SiO, rotated clockwise to be aligned with the x-axis. As seen in Lee et al. (2009), the jet is highly collimated and consists of a chain of knotty shocks.

4.1. Line Polarization and Field Morphology

The figure also shows the polarization intensity map and vectors in the jet in the SiO line. The angles of the polarization vectors have an uncertainty of $\sim 13^\circ$. The line polarization can be attributed to the GK effect. In HH 211, the jet lies close to the plane of the sky. For the SiO $J = 8–7$ emission, the optical depth is close to 1 and the radiative transition rate is greater than the collision rate in most regions (Lee et al. 2009). All of these are optimal for polarization detection and thus the polarization degree could exceed 10% (Kylafis 1983), as seen in the observation. Two polarization detections, one in knot RK2 and one between knots BK2 and BK3, are greater than 3$\sigma$, and thus should be real. Their polarization vectors have different orientations, with the former parallel to the jet axis and the latter inclined by $\sim 50^\circ$ to the jet axis. Other detections are below 3$\sigma$ and thus should be considered tentative. No polarization is detected toward the bright innermost pair of knots, probably because of the higher density there than other regions.

According to the GK effect, the field could be either parallel or perpendicular to the polarization vector, depending on the angle $\delta$ between the velocity flow axis and the polarization vector (Kylafis 1983). If $35.3^\circ < \delta < 54.7^\circ$, the field direction is parallel to the polarization vector. If $0^\circ < \delta < 35.3^\circ$, then there is
a 90° ambiguity in the field direction. In the jet, the velocity flow axis is the same as the jet axis. The polarization vectors between knots BK2 and BK3 have \( \delta \approx 50° \), thus the field lines there are parallel to the polarization vectors, highly inclined to the jet axis, and thus could be helical. In knot RK2, the polarization vectors are almost aligned with the velocity flow axis. In this case, the field lines could be either parallel or perpendicular to the polarization vectors. Therefore, the fields there could be either poloidal or toroidal.

4.2. Discussion

In knot RK2, there is a sufficient number of polarization vectors for us to estimate the magnetic field strength there. According to Chandrasekhar & Fermi (1953) and Ostriker et al. (2001), we can estimate the field strength in the plane of the sky with the following formula:

\[
B \sim 0.5 \sqrt{4\pi \rho \frac{\Delta v_{\text{los}}}{\Delta \phi}}. \tag{1}
\]

The mass density \( \rho = 1.4 n_H m_H \sim 4.64 \times 10^{-16} \text{ g cm}^{-3} \), with \( n_H \sim 10^7 \text{ cm}^{-3} \) (Lee et al. 2009). The velocity dispersion along the line of sight \( \Delta v_{\text{los}} \sim 10 \text{ km s}^{-1} \) (Lee et al. 2009). With the dispersion of the polarization angle \( \Delta \phi \sim 20° \pm 13° \) (including the uncertainty in the angle of the polarization vectors), we have \( B \sim 35^{+65}_{-10} \text{ mG} \). As discussed earlier, the field there could be toroidal. According to Shu et al. (1995), the toroidal field strength in an originally unshocked jet material could be \( \gtrsim 7 \text{ mG} \) for the HH 211 jet, which has a radius of \( \lesssim 20 \text{ AU} \) (Lee et al. 2009). Thus, if the field in knot RK2 is purely toroidal, our estimated field strength there is about 5 times as high, probably not unreasonable considering a shock compression. The magnetic pressure due to this toroidal field is \( B^2/8\pi \sim 3 \times 10^{-5} \text{ dyne cm}^{-2} \). The thermal pressure there is \( 1.2 n_H kT \sim 8 \times 10^{-7} \text{ dyne cm}^{-2} \), with \( T \sim 500 \text{ K} \) (Lee et al. 2009), much lower than the magnetic pressure. Hence, the jet material there should be well confined by the magnetic field, if the field there is really toroidal.

Magnetic field morphology in a protostellar jet is still poorly determined due to a lack of polarization detection. Previously, Carrasco-González et al. (2010) detected linear polarization in the synchrotron jet HH 80-81 from the high-mass protostar IRAS 18162-2048 and found that the field lines there are mainly aligned with the jet axis. They saw an increase in the polarization degree toward the jet edges and argued that it was due to the helical field toward the jet edges. However, the jet with the polarization detection is far, at \( \sim 0.5 \text{ pc} \) away from the source, has an extremely large transverse width of \( \sim 40000 \text{ AU} \), and thus might not trace the intrinsic jet coming from the source (Esquivel & Raga 2013). In comparison, our polarization detections are within 2000 AU (\( \sim 7° \)) of the source. The jet is located inside an outflow cavity and has a transverse width of \( \lesssim 40 \text{ AU} \) (Lee et al. 2009), as expected for a jet coming from a low-mass protostar. Since the polarization detections here show different orientations in different regions, further observations with ALMA at higher sensitivity are really needed to confirm them and to determine the field morphology.

In conclusion, we might have detected for the first time polarized SiO line emission in the jet due to the GK effect. If confirmed, our detection will open the possibility that the GK effect can be used to infer magnetic field morphology in the jet in the early phase of star formation, in which the jet is primarily molecular. The inferred field morphology can then be used to constrain the jet launching models.

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