SAVING EARLY DISK FORMATION OF YOUNG STELLAR OBJECTS FROM THE MAGNETIC BRAKING CATASTROPHE

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ABSTRACT

Previous observations and ideal magneto-hydrodynamic (MHD) simulations have reported that magnetic fields aligned with the rotation axis, often the bipolar outflow direction, in the youngest protostellar systems prevent a rotationally supported disk from being formed due to efficient magnetic braking, which is known as the magnetic braking catastrophe. We carried out polarimetric observations of the Atacama Large Millimeter/submillimeter Array (ALMA) toward the youngest protostellar system L1448 IRS 2, which is a proto-binary embedded within a flattened, rotating structure, and for which a hint of a central disk has been suggested, but whose magnetic fields are aligned with the bipolar outflow. Our high sensitivity observations show a beautiful hourglass morphology of magnetic fields in the protostellar system, with a toroidal field at the center, which is strong evidence for a circumstellar disk. We have also found a relationship between polarization fractions and intensities, which has various slopes that can be understood through multiple polarization mechanisms, optical depth effects, and depolarization due to field changes. In addition, we found clumpy strips crossing the center perpendicular to the bipolar outflow. Moreover, the magnetic field strength estimated by the Davis-Chandrasekhar-Fermi method is strong enough to hinder formation of a rotationally supported disk, which is inconsistent with the central toroidal field. We conclude that in this source the magnetic braking is not so catastrophic and that non-ideal MHD effects should be considered for a better understanding of early disk and companion star formation in young stellar objects.

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1. INTRODUCTION

Magnetic fields are thought to play a significant role in star formation on all scales from the cloud to the disk. For example, it has been found that magnetic field directions are well ordered and typically perpendicular to parsec-scale filamentary structures (e.g., Palmeirim et al. 2013), which indicates that magnetic fields are important to form such intermediate scale structures. Also, the magnetic energy is comparable to the kinetic energy down to a few thousand au scales (e.g., Li et al. 2014; Pattle et al. 2017).

In addition, magnetic fields can affect circumstellar disk formation at the early protostellar stages. Hull et al. (2013) found that magnetic field directions of 16 young stellar objects (YSOs) are rather random with respect to their bipolar outflows on a few hundred au scales, although a couple of examples with hourglass morphology magnetic fields aligned to its bipolar outflow had been known at the time (Girart et al. 2006; Stephens et al. 2013). Later, it has been suggested that the magnetic field directions of YSOs can be understood with the existence of an extended disk structure at the youngest YSOs, the so-called Class 0 YSOs (e.g., Segura-Cox et al. 2015). For example, L1527 has a magnetic field morphology perpendicular to the bipolar outflow and has an extended Keplerian disk (radius \( \sim 54 \) au) (Tobin et al. 2012; Hull et al. 2013; Ohashi et al. 2014), whereas L1157 that has a magnetic field aligned with the bipolar outflow has no disk structure larger than 15 au (Stephens et al. 2013; Tobin et al. 2013). Such features have been explained by magnetic braking, which can be so efficient in YSOs having a magnetic field aligned with the bipolar outflow that a rotation-supported disk structure is largely suppressed at the early stages (e.g., Mellon & Li 2008; Hennebelle & Ciardi 2009; Joos et al. 2012; Maury et al. 2018), often called the magnetic braking catastrophe.

However, not all Class 0 YSOs fit the interpretation connecting the magnetic field morphology and the disk structure. For example, although a rotating disk-like structure has been detected around L1448 IRS 2 and its central binary companion (e.g., Tobin et al. 2015), the magnetic field direction detected in 500–1000 au scales is mostly aligned with the bipolar outflow (Hull et al. 2014), in which magnetic braking is expected to be efficient. In addition, Davidson et al. (2014) reported that the most preferred magnetic field for the Class 0 YSO L1527, which has a large Keplerian disk (Tobin et al. 2012; Ohashi et al. 2014), is a weak field aligned with the bipolar outflow, not a perpendicular field, when considering magnetic fields of large \( \sim 3000 \) au scales as well as small \( \sim 500 \) au scales. On the other hand, as an example, Machida et al. (2014) reported that the magnetic braking effect depends on density distributions of the dense cores that collapse to form the YSOs as well as magnetic field morphologies. In addition, they found that numerical simulations using a large sink radius suppress disk formation at the early evolutionary stages. Also, non-ideal magneto-hydrodynamic (MHD) effects (e.g., Ohmic dissipation) can enable the formation of a rotationally supported disk even in the case of a magnetic field aligned with the bipolar outflow that has efficient braking in the ideal MHD simulations.

An obvious way to investigate whether primordial magnetic field morphologies affect disk formation at the early evolutionary stages is to examine the small scale fields of those YSOs that have envelope-scale (1000–10000 au) fields aligned with the bipolar outflow. In this paper, we report polarimetric observations of the Atacama Large Millimeter/submillimeter Array (ALMA) toward L1448 IRS 2 focusing on how the magnetic fields change in 100 au scales.

2. TARGET AND OBSERVATIONS
Several Class 0 YSOs with flattened envelope structures have been identified by Tobin et al. (2010) in the Perseus molecular cloud at a distance of about 230 pc (Hirota et al. 2011). Of these envelopes, L1448 IRS 2 has the clearest flattened structure and has been observed in polarization indicating a magnetic field aligned with the bipolar outflow (Hull et al. 2014). Previous studies have imaged a largely extended bipolar outflow originating from the target at various wavelengths: e.g., near IR observations using the Spitzer Space Telescope (Tobin et al. 2007). In addition, Kwon et al. (2009) reported that grains have significantly grown based on the dust opacity spectral index estimated from 1 and 3 mm observations of the Combined Array for Research in Millimeter-wave Astronomy (CARMA). Regarding polarimetric observations, Caltech Submillimeter Observatory SHARP observations detected 350 µm continuum polarization perpendicular (inferred magnetic field\textsuperscript{1} parallel) to the bipolar outflow with a 10″ angular resolution (Chapman et al. 2013). Hull et al. (2014) also detected polarization in the same direction, particularly in the blueshifted lobe on the northwest side from the center with an angular resolution of ~2″.

Polarimetric observations toward L1448 IRS 2 in ALMA Band 6 were made on 2016 November 12 and 14 (2016.1.00604.S, PI: Woojin Kwon). Individual tracks were run over 3 hours to achieve a good parallactic angle coverage. HH 211 was observed simultaneously with L1448 IRS 2 and shared the same phase calibrator; HH 211 will be reported in a separate paper. The November 12 and 14 tracks have 42 and 40 antennas in the array, respectively. J0238+1636 was used as polarization calibrator and flux calibrator. Its flux was set to 1.085 Jy at 233 GHz with a spectral index of about -0.45. J0237+2848 and J0336+3218 were bandpass and phase calibrators, respectively. All the execution blocks were calibrated separately and combined when making images. Images were made using a Brigg’s weighting with a robust parameter of 0.5. We found this weighting was a good compromise between resolution and sensitivity. The final image has a synthesized beam of 0′′.57 × 0′′.37 (PA = 9.14°). The noise levels of Stokes I (total intensity), Q, and U maps are ~0.10, ~0.014, and ~0.014 mJy beam\textsuperscript{-1}, respectively.

3. RESULTS

3.1. Magnetic field morphology

Although we assume that the polarization is due to magnetically aligned dust grains, we are aware that dust polarization can in principle be produced by other mechanisms, even at millimeter wavelengths, such as alignment with the radiation anisotropy (e.g., Tazaki et al. 2017) and self-scattering (e.g., Kataoka et al. 2015; Yang et al. 2017; Stephens et al. 2017b). However, these effects, especially scattering, are inferred to be present in disks that have large grains. Currently, there is no compelling evidence that they play a significant role outside the disk. We explicitly indicate whether polarization E vectors\textsuperscript{2} or inferred B vectors are plotted.

The magnetic field morphology shows a beautiful hourglass morphology perpendicular to the elongated structure as shown in Figure 1. Consistent with previous CARMA observations (Hull et al. 2014), the region northwestern of the center shows a poloidal field, which is approximately aligned with the bipolar outflow direction. However, in the central region the field direction rapidly changes to an orientation perpendicular to the bipolar outflow, which is consistent with the polarization pat-

\textsuperscript{1} Assuming magnetic field grain alignment, the magnetic field directions are inferred by 90° rotation of polarization directions.

\textsuperscript{2} Although they are not actual vectors since their directions have a 180° ambiguity, we use the convention of calling them vectors.
tern produced by grains aligned with a toroidal magnetic field close to the protostar. This could also be interpreted as a self-scattering polarization feature. Note that the self-scattering polarization pattern is expected to be parallel to the minor axis of an inclined disk (e.g., Yang et al. 2016; Kataoka et al. 2017; Stephens et al. 2017b), which means that after 90° rotation, the corresponding B vectors look like a toroidal feature. If the toroidal field interpretation is correct, it would indicate that rotation has become fast and energetic enough to wind up the field lines, which likely signals the formation of a rapidly rotating disk. If the dust self-scattering interpretation is correct, it would indicate that grains in the flattened structure on the scale of several tens au have grown to roughly 100 µm sizes or more, which again would favor the existence of a rotationally supported disk that is conducive to grain growth through a higher density and longer time compared to a dynamically collapsing inner envelope. Recently, some other ALMA polarimetric observations have also presented polarization patterns of self-scattering or toroidal magnetic fields in the central regions of Class 0 and I YSOs with a disk (Lee et al. 2018) and disk candidates (Cox et al. 2018). By the way, we have selected polarized signals detected at 2σ levels or better and debiased using the noise levels of Stokes Q and U maps 0.014 mJy beam$^{-1}$. The vectors are marked every 0.21″, which is comparable to the Nyquist sampling.

The contours in the right panel of Figure 1 also show the binary companion (L1448 IRS 2B), which is separated from the primary by about 0.6″ (corresponding to ~ 140 au at the target distance) toward the west. This companion is less bright in the 1 mm continuum. Tobin et al. (2016) detected the companion at 9 mm (Ka-band), but it has not been detected at 1 mm before. The blue and red contours overlaid in the figure are CO 2-1 molecular line data taken by ALMA (2013.1.00031.S;
Figure 2. Stokes Q, Stokes U, and polarization intensity maps are on left, in the middle, and on right, respectively. The contours present distributions of total intensity (Stokes I) at the same levels of Fig. 1.

Tobin et al. in prep.). The angular resolution of the CO 2-1 observations is $0\farcs35 \times 0\farcs25$ (PA: 21°), which is slightly better than the polarimetric continuum data. Since these observations lack short baselines, only the cavity walls were detected, as the extended features between the walls (as detected in Tobin et al. 2015) are filtered out. Interestingly, the less bright companion L1448 IRS 2B seems to be more coincident with the bipolar outflow. While the redshifted lobe is primarily centered on the combination of both L1448 IRS 2A and 2B, the main blueshifted lobe seems to be centered on L1448 IRS 2B only. However, there is a weak blueshifted feature from the L1448 IRS 2A and along the left continuum branch. It is possible that the blueshifted component from L1448 IRS 2A might be in the same velocity regime of the ambient cloud and thus could be filtered out by the interferometer.

3.2. Polarization intensity and fraction

In Figure 2, the outflow cavity walls have relatively high polarization intensities, while there is a strip across the center, almost perpendicular (P.A. $\sim 35^\circ$) to the bipolar outflow (P.A. $\sim 118^\circ$ at large scales; Stephens et al. 2017a), with weak polarization signal lower than a few tens $\mu$Jy beam$^{-1}$. This depolarized strip is shown in more detail in Figure 3 and discussed below. The polarization intensity is not symmetrically distributed. The central region of the total intensity peak has the highest polarization intensity. Also, the region south of the depolarized strip to the east of the center is high in polarization intensity. In addition, polarization intensity is very clumpy compared to the total intensity distributions, which is indicative that polarization is significantly affected by the local environment.

As shown in Figure 3, the depolarization regions of L1448 IRS 2 clearly appear at the central region and along the strip perpendicular to the bipolar outflow, whose polarization fractions are only a few percent or less. The central region with the binary system presumably has the most complicated magnetic fields. Also, as addressed, the magnetic fields are changing from aligned to perpendicular to the bipolar outflow going from large to small scales. These complicated polarization patterns that are smaller than the beam reduce the measured polarization fraction: i.e., beam smearing. On the other hand, the depolarized strip is similar to the case of inclined disks (Kataoka et al. 2012). This is not surprising since the blue- and red-shifted CO outflows indicate a moderate inclination. Indeed, Tobin et al. (2007) reported that the bipolar outflow is inclined by about 57° (where 90° indicates a bipolar outflow on the sky plane). The inferred inclination makes it possible for the radially pinched
Figure 3. Polarization fraction distribution indicated in color scales. The other plot components are the same to Fig. 1. The schematic diagram in the right illustrates hourglass morphology magnetic fields detected in different alignment: small scales in red and large scales in blue.

Field lines along a given line of sight to produce polarizations that cancel one another, yielding a less polarized equatorial region (see Fig.6d of Kataoka et al. 2012), which is broadly consistent with the depolarization strip to the northeast of the center. This interpretation is strengthened by the fact that the field direction changes sharply across the depolarization strip, consistent with the generation of a significant radial component of the magnetic field by the gravitational infall of the protostellar accretion flow, as illustrated for example by Figure 7 of Kataoka et al. (2012). Depolarization can also occur due to high optical depth (see Fig.3 of Yang et al. 2017), but this is not likely the case here since the optical depth is expected to be low along this depolarization strip: $\tau \sim 0.08$ even at the highest contour level assuming $T = 30$ K.

In addition, along the depolarized strip, there are several depolarized clumps, whose sizes are not resolved at our angular resolution, as seen in the yellow and white in Fig. 3. The clumps are separated by $\sim 0.8''$, which corresponds to about 180 au at the distance of Perseus. These clumps may indicate relatively more turbulent areas with chaotic magnetic fields and/or areas with magnetic fields pointing along the line of sight direction. They may even be regions of de-magnetized “islands” produced by reconnection of sharply pinched magnetic field lines (see Fig. 7 of Suriano et al. 2017), although detailed exploration of magnetic reconnection is beyond the scope of this letter.

The highest polarization fractions, reaching levels of up to 40%, are located near the border of the northwest and southeast part of the envelope. Such high polarization fractions can occur only by
very elongated, aligned dust grains (e.g., axis ratios larger than 3; private communication with T. Hoang). Based on the high polarization fraction locations, we speculate that mechanical alignment could also contribute to the polarization in the cavity walls. In the case of mechanical alignment, it has recently been suggested that the spinning, minor axis of elongated dust grains are aligned with the mechanical flow (Hoang et al. 2018), in contrast to the classical mechanical alignment (Gold 1952). Therefore, the polarization directions are the same to the dust grains aligned in poloidal magnetic fields along the bipolar outflow. In addition, the continuum structure is more extended in Stokes I than those in Stokes Q and U, as shown in Figure 2. This results in more flux of Stokes I filtered out, so contributes to the high polarization fractions as well, particularly at the edges.

Figure 4 shows the relationship between polarization fractions ($P_{frac}$) and Stokes I intensities ($I$). When polarization emission is dominated from the surface of a structure, the polarization fraction is expected to be inversely proportional to the intensity: $P_{frac} \propto I^{-1}$: e.g., polarization caused by dust grains aligned by magnetic fields due to the interstellar radiative torque (RAT, Lazarian & Hoang 2007) mainly around the molecular cloud surface. Interestingly, Figure 4 shows multiple slopes that encompass the limits of the distributions. In the regime fainter than about 1 mJy beam$^{-1}$, the slope is roughly $-0.4$. This region corresponds to the area from the second lowest contour to about the fourth contour in the 1 mm continuum map of Figure 3. The slope shallower than $-1$ could be interpreted with additional polarization contributions from these areas (as addressed above, e.g., mechanical alignment), not just on the structure surface. Between $\sim 1$ and $\sim 10$ mJy beam$^{-1}$, the slope is close to $-1$, which is indicative that the regions have no further significant polarization. Approaching to 10 mJy beam$^{-1}$, the slope becomes a little bit steeper than $-1$: $s = -1.3$. This can be interpreted as polarization directions changing, resulting in depolarization. Indeed, the region is where the field directions switch from the poloidal to the toroidal pattern. For the central region that is brighter than 10 mJy beam$^{-1}$ the slope is $-0.5$. This shallower slope may be caused by a more efficient grain alignment closer to the central stars through RAT. In addition, presumably self-scattering may also contribute to the polarization fraction at these scales (e.g., Kataoka et al. 2017; Stephens et al. 2017b, 2014).

4. DISCUSSION

4.1. Magnetic field strength

We estimate the magnetic field strength using the Davis-Chandrasekhar-Fermi (DCF) method (Davis 1951; Chandrasekhar & Fermi 1953). We are aware that the field orientations can be affected by outflows and gravitational collapse, but such effects require more detailed dynamical modeling that is beyond the scope of this letter. In the DCF technique, the magnetic field strength is estimated based on the dispersion of magnetic fields with respect to the background field direction compared to its turbulence in a given density medium. In other words, a medium at a given density and a turbulence indicated by a non-thermal linewidth would have a stronger magnetic field strength when it has a smaller field position angle dispersion: the plane-of-sky strength of a magnetic field $B_{POS} = Q \sqrt{4\pi \rho \delta V / \delta \phi} \approx 9.3 \sqrt{n(H_2) \Delta V / \Delta \phi} \, [\mu G]$, where $Q$, $\rho$, $\delta V$, $\delta \phi$, and $n(H_2)$ are a factor of order unity, the gas density, the non-thermal velocity dispersion in km s$^{-1}$, the position angle dispersion of polarizations, and the molecular hydrogen number density, respectively (e.g., Crutcher et al. 2004; Ostriker et al. 2001). We follow the application of the DCF technique outlined in Pattle et al. (2017).
Figure 4. Polarization fraction versus intensity. Each blue circle represents a pixel value, and the black lines indicate individual power-law slopes, not fitting results. Data points of intensities greater than 3σ and polarization intensities larger than 2σ have been selected.

First, for the background large-scale fields we smoothed the Stokes Q and U maps with a three-times larger beam (extended in both major and minor axes of the original beam by a factor of three), which is comparable to a half of the width across the continuum structure. This provides a reasonable background field morphology (Pattle et al. 2017). As Figure 5 shows, the smoothed fields in white vectors do not show the toroidal switch at the central region. Since we know the central area is confused by the morphological change and possible polarization contamination from scattering, we only apply the DCF method to the areas between intensities of 0.3 and 6.5 mJy beam$^{-1}$ (thick gray contours in Figure 5). The measure dispersion is estimated as 10$^\circ$ (Fig. 5, right). Second, for estimating the number density of H$_2$ we utilized the dust continuum. The total continuum flux density of the area between 0.3 and 6.5 mJy beam$^{-1}$, which is 18.2 squared arc-seconds, is about 91 mJy at 233 GHz. The total mass is estimated by $M_T = F_\nu D^2/\kappa_\nu B_\nu(T_d)$, where $F_\nu$, $D$, $\kappa_\nu$, $B_\nu$, and $T_d$ are the flux density, distance, mass absorption coefficient, blackbody radiation intensity, and dust temperature, respectively. Using $F_\nu = 91$ mJy, $D = 230$ pc, $\kappa_\nu = 0.01$ cm$^2$ g$^{-1}$ at 233 GHz (Ossenkopf & Henning 1994) assuming a gas-to-dust mass ratio of 100, and $T_d = 30$ K (Kwon et al. 2009), the total mass is estimated to be 0.05 M$_\odot$. In addition, assuming a cylinder with the profile of the continuum feature, the total volume would be $4 \times 10^{48}$ cm$^3$. Therefore, we derive the volume density $\rho \approx 2.5 \times 10^{-17}$ g cm$^{-3}$, which corresponds to $n(H_2) \approx 7.5 \times 10^6$ cm$^{-3}$. We do not have an
observational non-thermal linewidth, but it may be reasonable to adopt the trans-sonic velocity at 30 K: \( \sim 0.3 \text{ km s}^{-1} \). These values result in the magnetic field strength in the plane of sky about 750 \( \mu \text{G} \), with the relationship following:

\[
B_{POS} \approx 750 \ \mu \text{G} \left( \frac{n(H_2)}{7.5 \times 10^6 \text{cm}^{-3}} \right)^{0.5} \left( \frac{\Delta V}{0.3 \text{ km/s}} \right) \left( \frac{10^5}{\delta \phi} \right). \tag{1}
\]

Furthermore, we estimate the magnetic braking time scale of the presumed disk structure at the center, when the rotation velocity decreases by a half. The Alfvén speed follows the relationship,

\[
v_A = \frac{B}{\sqrt{4\pi \rho}} = 0.4 \ \text{km/s} \left( \frac{B}{750 \ \mu \text{G}} \right) \left( \frac{2.5 \times 10^{-17} \text{g/cm}^3}{\rho} \right)^{0.5}. \tag{2}
\]

In addition, the central mass surrounded by the inner thick gray contour in Figure 5 is estimated as 0.03 \( \text{M}_\odot \) based on the total flux density of 55 mJy. Since the central region is warmer than the outer region, this mass is an upper limit. Also, the central rotating structure could be much smaller than the inner region considered here. The same mass beyond the central area is extended up to the intensity of \( \sim 0.0011 \text{ mJy beam}^{-1} \), which is about 0.5'' (115 au) away. When the Alfvén wave reaches this point, the rotating mass tied up by the magnetic field is doubled so the rotation velocity becomes a half assuming angular momentum conservation. This timescale is calculated to be \( \sim 1400 \) years. Note that this is an overestimate because of the upper limit mass but still much shorter than the age of Class 0 YSOs, which is several thousands years. Even further, when regarding the canonical accretion rate of Class 0 YSOs \( \sim 10^{-6} \text{ M}_\odot \text{ year}^{-1} \) (e.g., Shu 1977; Dunham et al. 2014), the magnetic braking effect, which slows down 0.03 \( \text{M}_\odot \) in 1400 years, dominates the system. Taken at the face value, the estimated field strength is high enough for the magnetic field to brake the disk rotation efficiently. However, as we mentioned earlier, the polarization orientations on the several tens au scale are indicative of a disk. If true, the existence of a relatively large disk in the presence of a strong inferred magnetic field would point to a decoupling of the field from the bulk disk material, most likely through non-ideal MHD effects, which become more important at higher densities.

5. CONCLUSION

We have detected an incredibly well-ordered polarization pattern toward the Class 0 YSO L1448 IRS 2, whose inferred magnetic field presents the clearest hourglass morphology to date: poloidal in the outer regions and rapidly switching to toroidal in the inner region. This can be interpreted as a toroidal magnetic field wrapped up by a rotating (disk) structure or by a self-scattered polarization pattern due to large grains in an inclined disk: either case supports a rotationally dominant structure. Future high resolution molecular line observations are needed to investigate whether there is a rotationally supported disk.

We found four regimes with different slopes in the relationship between polarization fractions and intensities, which provide interesting constraints on grain alignment mechanisms. In addition, we detected depolarized clumpy strips, which are indicative of magnetically channelled protostellar accretion flows which drag the field lines into a radially pinched configuration that, when combined with inclination effects, lowers the degree of polarization.

Finally, we estimated the plane-of-sky magnetic field strength using the DCF technique and found that magnetic braking should be very efficient in the system, which is inconsistent with the strong
Figure 5. Intensity map in color scales. Magnetic fields of the original angular resolution are marked in gray and fields smoothed by three times larger beams are in white. Refer to the text for the thick gray contours lines. In the right is the histogram of the magnetic field dispersion.

hints of a central disk, protobinary, and observations of rotation. Therefore, the magnetic braking catastrophe based on ideal MHD simulations may not be so disastrous. To fully understand the formation of disks at the early protostellar systems, non-ideal MHD effects should be taken into account.

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Facilities: ALMA

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