ANGULAR MOMENTUM LOSS IN THE ENVELOPE–DISK TRANSITION REGION OF THE HH 111 PROTOSTELLAR SYSTEM: EVIDENCE FOR MAGNETIC BRAKING?

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ABSTRACT

HH 111 is a Class I protostellar system at a distance of ~400 pc, with the central source VLA 1 associated with a rotating disk deeply embedded in a flattened envelope. Here we present the observations of this system at ~0′′6 (240 au) resolution in C18O (J = 2 − 1) and a 230 GHz continuum obtained with the Atacama Large Millimeter/Submillimeter Array, and in SO (N_J = 5_6 − 4_5) obtained with the Submillimeter Array. The observations show for the first time how a Keplerian rotating disk can be formed inside a flattened envelope. The flattened envelope is detected in C18O, extending out to >2400 au from the VLA 1 source. It has a differential rotation, with the outer part (>2000 au) better described by a rotation that has constant specific angular momentum, and the innermost part (<160 au) by a Keplerian rotation. The rotationally supported disk is therefore relatively compact in this system, which is consistent with the dust continuum observations. Most interestingly, if the flow is in steady state, there is a substantial drop in specific angular momentum in the envelope–disk transition region from 2000 to 160 au, by a factor of ~3. Such a decrease is not expected outside a disk formed from simple hydrodynamic core collapse, but can happen naturally if the core is significantly magnetized, because magnetic fields can be trapped in the transition region outside the disk by the ram pressure of the protostellar accretion flow, which can lead to efficient magnetic braking. In addition, SO shock emission is detected around the outer radius of the disk and could trace an accretion shock around the disk.

Key words: circumstellar matter – ISM: individual objects (HH 111) – stars: formation

1. INTRODUCTION

Keplerian rotating disks (KRDs), which are rotationally supported, have been detected around young stellar objects, especially in the Class II and Class I phases. Recently, more and more such disks have been found, as early as in the Class 0 phase (Lee et al. 2009, 2014; Murillo et al. 2013; Ohashi et al. 2014). However, the formation mechanism of such disks is still not well understood because of a lack of observations at high angular and velocity resolutions.

A few years ago, through Submillimeter Array (SMA) observations, the rotation profile in the Class I source HH 111 was found to transition from conserved angular momentum in the envelope to Keplerian in the KRD (Lee 2010). This transition was found for the first time in star formation, providing a clue to the formation mechanism of KRDs. With the Atacama Large Millimeter/Submillimeter Array (ALMA), recent searches also found such transitions, even in Class 0 sources, e.g., L1527 IRS (Ohashi et al. 2014; Sakai et al. 2014) and HH 212 (Lee et al. 2014). In order to study how a KRD can be formed, we need to resolve the transition region and compare its structure and kinematics to current model predictions.

Theoretically, in models of non-magnetized core collapse, a KRD can indeed form as early as in the Class 0 phase (Terebey et al. 1984). However, a realistic model should include a magnetic field, because a recent survey toward a few Class 0 sources showed that molecular cores are magnetized and likely to have an hourglass B-field morphology (Chapman et al. 2013). Unfortunately, in many current models of magnetized core collapse, the magnetic field produces efficient magnetic braking that removes the angular momentum and thus prevents a KRD from forming at the center (Allen et al. 2003; Mellon & Li 2008; Galli et al. 2009). In those cases, only a flattened envelope called the pseudodisk can form around the central source (e.g., Allen et al. 2003). Magnetic-field-rotation misalignment is sometimes able to solve this so-called magnetic braking catastrophe (Joos et al. 2012; Li et al. 2013), but not always.

This paper is a follow-up study of the transition region in the HH 111 protostellar system. The properties of this system have been reported in Lee (2011) and only the important ones are summarized here. This system is deeply embedded in a compact molecular cloud core in the L1617 cloud of Orion at a distance of 400 pc. At the center of this system, there are two sources, VLA 1 and VLA 2, with a projected separation of ~3″ (1200 au) and the former driving the prominent HH 111 jet (Reipurth et al. 1999). The VLA 1 source is a Class I protostellar system with a flattened envelope, a rotating disk, and a highly collimated jet. Previous SMA observation of this system in C18O has shown that the flattened envelope is in transition to a KRD near the VLA 1 source (Lee 2010). No clear influence of the VLA 2 source was seen on the envelope and disk of the VLA 1 source. This is a follow-up study of this system with about two times higher angular resolution and about three times higher velocity resolution in C18O (J = 2 − 1) obtained with ALMA at about eight times higher sensitivity. In addition, to augment our study, we also include SO (N_J = 5_6 − 4_5) shock emission at a similar angular resolution obtained with the SMA. This study shows for the first time the resolved region of the transition, where a disk can be formed inside an envelope.
2. OBSERVATIONS

2.1. ALMA Observations

Observations toward the HH 111 system were obtained with ALMA using both the 12 m array (in the C32-4 configuration with a total time of ~140 minutes) and the 7 m array (with a total time of ~445 minutes). This project was a Cycle 1 project transferred to Cycle 2. For the 12 m array, three executions were carried out during 2014 April 13–28, all with 47.11 minutes on the source. Thirty-three to 35 antennas were used with the projected baseline length of 20–558.2 m. For the 7 m array, 20 executions were carried out, with five during the 2013 December 14–15, four during 2014 January 11–15, five during 2014 April 09-May 03, and six during 2014 December 11–14, all with 22.37 minutes on the target source, except for one with 19.47 minutes. Eight to ten antennas were used with the projected baseline length of 7–48.9 m. A three-point mosaic was used to cover ~40′′ to the north and south from the center, observing the envelope and disk in the equatorial plane of the system.

The 230 GHz band receivers were used to observe the $^{12}$CO ($J = 2 - 1$), $^{13}$CO ($J = 2 - 1$), and C$^{18}$O ($J = 2 - 1$) lines simultaneously with the 230 GHz continuum. Note that the $^{12}$CO and $^{13}$CO lines trace mainly the outflow and will be presented in a future publication. The velocity resolution in C$^{18}$O is ~0.083 km s$^{-1}$.

The data were calibrated with the CASA package, with quasars J0750+1231 and J0607-0834 as passband calibrators, quasars J0532 + 0732 (a flux of 1.40 ± 0.14 Jy) and J0607-0834 (a flux of 0.63 ± 0.07 Jy) as gain calibrators, and Callisto and Ganymede as flux calibrators. With super-uniform weighting and taper, the synthesized beam becomes circular with a size of 0.50'' in continuum. With super-uniform weighting, the synthesized beam has a size of 0''74 × 0''62 at a position angle (P.A.) of 77° in C$^{18}$O. The rms noise level is ~0.22 mJy beam$^{-1}$ (~20 mK) for the continuum, and ~4.3 mJy beam$^{-1}$ (~0.23 K) for the C$^{18}$O channel maps at ~0.083 km s$^{-1}$ velocity resolution. The velocities in the channel maps are LSR.

2.2. SMA Observations

For SO observations with SMA, the details have been reported in Lee (2011) and are thus not repeated here. The longest projected baseline length is ~480 m, similar to that of ALMA observations. The velocity resolution in the SO line is ~0.28 km s$^{-1}$ per channel. Only one single pointing toward the central region was observed to map the inner part of the envelope and disk. The visibility data were calibrated with the MIR package. The flux uncertainty was estimated to be ~15%. The calibrated visibility data were then imaged with the MIRIAD package, as described in Lee (2011). With super-uniform weighting, the synthesized beam has a size 0''67 × 0''57 with a P.A. of 75°. The rms noise levels are ~35 mJy beam$^{-1}$ (~2.3 K) in the channel maps. The velocities in the channel maps are LSR.

3. RESULTS

As in Lee (2010), the results are presented in comparison to a mosaic image based on the Hubble Space Telescope (HST) NICMOS image (Fe II) 1.64 μm + H$_2$ at 2.12 μm + continuum) obtained by Reipurth et al. (1999), which shows two VLA sources in the infrared, reflection nebulae that trace the illuminated outflow cavity walls, and the jet in the system. The two sources have been detected at the very high angular resolution of ~0''05 in the 7 mm continuum by the VLA as the VLA 1 and 2 sources, respectively, at α(2000) = 05h 46m 25s, δ(2000) = +02° 48’ 29” 65’, and α(2000) = 05h 46m 07s, δ(2000) = +02° 48’ 30” 76” (Rodríguez et al. 2008). These VLA sources are adopted here as the source positions. Based on the fitting of the rotation curve in the envelope (Section 3.2), the systemic velocity in this region is refined to be $V_{\text{sys}} = 8.85 ± 0.14$ km s$^{-1}$ LSR, from 8.9 ± 0.14 km s$^{-1}$ found in Lee (2010) at a three times lower velocity resolution. Throughout this paper, we define an offset velocity $V_{\text{off}} = V_{\text{LSR}} - V_{\text{sys}}$ to facilitate our presentation.

3.1. 230 GHz Continuum Emission

Figure 1 shows the 230 GHz continuum map obtained with ALMA toward the VLA 1 and 2 sources. The synthesized beam has a size of 0''5. The arrows indicate the orientations of the blueshifted (western) and redshifted (eastern) components of the jet, respectively, from the VLA 1 source. The dashed line indicates the equatorial plane perpendicular to the jet axis. The contour levels are $2^{\alpha_h}P$, where $P = 173.8$ mJy beam$^{-1}$, which is the peak value at VLA 1, and $n = 1, 2, ...$. The thick contour highlights the value at 50% of the peak.

Figure 2 shows the C$^{18}$O spectrum toward the VLA 1 source averaged over an elliptical region of 2'' × 1'' elongated along the equatorial plane (P.A. = 6°7). The spectrum shows a
double-peaked line profile with a blue asymmetry and an absorption dip deepest at ~0.2 km s$^{-1}$, similar to that seen before extracted from the 1$''$/6 resolution SMA observation in Lee (2010). The blue asymmetry and absorption dip were used before to imply an infall motion in the envelope (Lee 2010). The brightness temperature near the systemic velocity is ~25% lower that found before, likely because part of the extended structure is resolved out in our observations at higher angular resolution. With ALMA sensitivity, the emission is now detected more than ±5 km s$^{-1}$ from the systemic, about 2 km s$^{-1}$ higher than that observed before with the SMA. As seen later, the emission at this high velocity arises near the source, allowing us to better constrain the Keplerian velocity near the source.

Figure 3(a) shows the C$^{18}$O total intensity map on top of the HST image. The emission extends mainly along the equatorial plane of the VLA 1 source, with some also extending to the NE, SE, SW, and NW around the outflow cavity walls, and some also extending to the west to the VLA 2 source. In the equatorial plane, C$^{18}$O emission shows an extended envelope detected up to ~12$''$ (4800 au) from the VLA 1 source. The more extended emission detected in our previous SMA observations (extending to ~16$''$, Lee 2010) is resolved out from our ALMA observations, due to a lack of shorter $uv$ coverage. The emission intensity increases toward the VLA 1 source, showing a flattened envelope (with a thickness of ~4$''$) formed within ~6$''$ of the source in the extended envelope. Interestingly, within this radius, the rotation velocity was found to transition to Keplerian velocity (Lee 2010). The intensity increases rapidly within ~1$''$–2$''$ of the VLA 1 source, suggesting for a final change in the structure from the (tenuous) flattened envelope to the (dense) disk. The envelope–disk is believed to be perpendicular to the jet that was found to have an inclination of ~10$^\circ$ to the plane of the sky (Reipurth et al. 1992) and is thus almost edge-on, with its farside to the west and nearside to the east.

Figure 4 shows the position–velocity (PV) diagram of the C$^{18}$O emission cut along the major axis of the envelope–disk in order to study the rotation velocity in the envelope–disk. In our previous study with SMA, the rotation velocity was found to increase toward the center, first with a profile corresponding to angular momentum conservation in the outer part and then with a Keplerian velocity profile in the inner part, with a change at the radius of ~5$''$ (Lee 2010). In particular, the outer part ($r$~5$''$–16$''$) could be fitted by $v_b = v_k (r/r_0)^{-1}$ with $v_k = 3.9 \pm 0.4$ km s$^{-1}$, while the inner part ($r \lesssim 5''$) by $v_b = v_k (r/r_0)^{-0.5}$ with $v_k = 1.75 \pm 0.2$ km s$^{-1}$, where $r_0 = 1''$. Now we can refine the fitting parameters with ALMA at higher angular and velocity resolutions. The rotation velocity in the outer part is found to follow the conservation of angular momentum down to ~±5$''$ as found before (marked as asterisks), but with slightly smaller $v_k = 3.6 \pm 0.5$ km s$^{-1}$ (solid curves). In this fit, the systemic velocity is refined to 8.85 km s$^{-1}$ from 8.9 km s$^{-1}$, in order to have a good fit on both the redshifted and blueshifted sides. Note that the value of $v_k$ could be smaller because the fit could be affected by the self-absorption and missing flux near the systemic velocity. However, the rotation velocity within ~5$''$ of the central source does not change to Keplerian immediately. Instead, as we go toward the central source, the rotation velocity first increases with a rate slower than that in the outer part and then decreases slightly (as indicated by the magenta lines in Figure 4(a)), and then increases rapidly toward the center, becoming Keplerian within ~0$''/4$ of the central source. The crosses at (0$''/4$, −3.1 km s$^{-1}$) and (−0$''/4$, 3.1 km s$^{-1}$) mark roughly the locations within which the rotation velocity can be reasonably described by the Keplerian velocity (dashed curves), with $v_k = 2.0 \pm 0.3$ km s$^{-1}$, slightly larger than that found before. Thereon, unlike in the previous study, only the very innermost part becomes a KRD. The region between ~5$''$ and 0$''/4$ can be considered as a transition region between the envelope and the disk. The Keplerian velocity here implies a mass of ~1.8 ± 0.5 $M_\odot$ for the central VLA 1 source. Note that there is a compact absorption dip centered at the VLA 1 source near the systemic velocity, which gives the absorption dip in the spectrum shown in Figure 2. As discussed in Lee et al. (2014) for HH 212, this compact absorption dip is likely due to an absorption of the continuum emission of the disk by the nearside of the envelope, which is found to be infalling toward the center (Lee 2010).

Figure 3(b) shows the high-velocity emission of C$^{18}$O, greater than ±3 km s$^{-1}$ from the systemic value, where the rotation velocity becomes Keplerian, as discussed earlier. The peaks of the blueshifted and redshifted emission are on the opposite sides of the VLA 1 source in the equatorial plane at a distance of ~0$''/3$, coincident with the radius of the dusty disk, further confirming that the disk is a KRD.

3.3. SO Shocks

In order to further investigate the transition region, we also plot in Figure 3(b) the SMA map of SO emission, which was argued to trace accretion shocks around the disk (Lee 2010). The SO emission was detected within 2$''$ of the VLA 1 source. In the equatorial plane, two SO emission peaks are seen on the opposite sides of the VLA 1 source, one at ~0$''/6$ and one at ~1$''/2$, near the edge of the high-velocity C$^{18}$O emission and dusty disk emission. In the south, SO emission is also seen closer in at ~0$''/4$ (160 au) extending to the SW from the disk, and may trace material (i.e., slow wind) coming out from the disk. In addition, SO emission is also seen extending to the
west, probably tracing material connecting to the VLA 2 source. SO emission is also seen extending to the NW, probably tracing the envelope or outflow around the cavity wall.

The PV diagram of the SO emission cut along the major axis is shown with the red contours in Figure 4(b). The SO emission is detected mainly within 2 km s\(^{-1}\) of the systemic velocity. The redshifted emission is mainly in the south, and blueshifted emission is mainly in the north, similar to those of the C\(^{18}\)O disk, suggesting that the shocked material traced by the SO emission is also rotating. On both blueshifted and redshifted sides the velocity of the emission increases toward the center (as indicated by the green lines), connecting to the C\(^{18}\)O emission at higher velocity, where the rotation velocity becomes Keplerian. This clearly suggests that SO shocks occur before the rotation velocity becomes Keplerian and the disk is formed. The SO emission closer in at −0\(\prime\)4 traces the base of the emission extending out from the disk to the SW (see Figure 3(b)). It is seen on both the blueshifted and redshifted sides in the PV diagram, tracing a shock at the base in the disk.

3.4. Infall Motion

Figure 5 shows the PV diagrams of C\(^{18}\)O and SO along the minor axis of the envelope–disk, in order to refine the infall motion in the envelope found in Lee (2010). As mentioned earlier, the envelope–disk is almost edge-on, with its farside to the west and nearside to the east. The flattened envelope has a thickness of ∼4″ and a radius of ∼6″. Thus, the C\(^{18}\)O emission beyond ±3″ from the center should be mainly from the outflow and is thus not shown here. In addition, the C\(^{18}\)O emission at < −2″ extends to the west to the VLA 2 source and is thus affected by the source. The SO emission at < −1″ extends to the west to the VLA 2 source (see Figure 3(b)) and is thus also affected by the source. As a result, both of these emissions should be excluded when studying the infall motion in the envelope. In C\(^{18}\)O, the blueshifted emission of the envelope is more on the west (farside) and the redshifted emission is more on the east (nearside), consistent with a small infall motion toward the VLA 1 source. That the blueshifted emission is brighter than the redshifted emission also supports the infall motion in the envelope. Since SO shows a similar velocity structure to C\(^{18}\)O, it can trace the infall motion as well. Assuming that the infall velocity in the envelope increases toward the center with \(r^{-0.5}\) as in Lee (2010), then the infall velocity seen in C\(^{18}\)O and SO can be roughly fitted with \(v_i = -1.7(r/r_0)^{-0.5}\) km s\(^{-1}\) (dashed curves).\(^4\) This infall velocity is ∼50% of the free-fall velocity due to the VLA 1 source (solid curves), which has a mass of ∼1.8 ± 0.5 \(M_\odot\) (as derived earlier from the Keplerian velocity of the disk).

\(^4\) Note that it was thought to be \(v_i = -0.7(r/r_0)^{-0.5}\) km s\(^{-1}\) in Lee (2010), due to incorrect correction for the projection effect.
4. DISCUSSION

4.1. Flattened Envelope: Transition Region

With ALMA observations in C$^{18}$O at higher angular and velocity resolutions, we can better constrain how a KRD can be formed around a forming star. The C$^{18}$O map shows a flattened envelope embedded in a more extended envelope. It has a radius of $\sim$6$''$ (i.e., 2400 au), slightly larger than the transition radius ($\sim$5$''$ or 2000 au) where the rotation profile starts to become flatter than that of the conservation of angular momentum. However, the rotation velocity does not change immediately to Keplerian at the transition radius. Instead, the rotation velocity first increases with a rate slower than that expected from the conservation of angular momentum, then decreases, and then increases rapidly near where the disk is formed. Therefore, the flattened envelope is mainly the transition region. The specific angular momentum, which is proportional to the product of rotation velocity and radius, decreases tremendously in the transition region, by a factor of $\sim$3 from a distance of roughly 2000 (5$''$)–160 au (0.4$''$) (see Figure 6 on the side of positive angular momentum). If the flow in the transition region is in steady state, the drop implies a tremendous loss of specific angular momentum, by a factor of 3. As a result, only a small KRD can be formed near the central VLA 1 source.

In the flattened envelope the infall velocity is not well determined, because the flattened envelope is almost edge-on and thus not well resolved along the minor axis. Nonetheless, the infall velocity derived here should be reasonable for the flattened envelope up to the transition radius, which has a projected distance of $\sim$0.9, resolvable with our observations. It is $\sim$50% of the free-fall velocity due to the VLA 1 source. Around the transition radius ($\sim$5$''$), it is $\sim$0.75 km s$^{-1}$, roughly the same as the rotation velocity there, which is $\sim$0.72 km s$^{-1}$. The complex rotation profile and substantial infall speed of the flattened envelope indicate that it is the transition region between the KRD (which is rotationally supported) and the more extended envelope, rather than the KRD itself.
The centrifugal radius of the envelope is where the centrifugal force is balanced by the gravitational force and is thus where the rotation velocity is equal to the Keplerian velocity. In our model, this radius is \[ \frac{v}{v_{\text{K}}} = \left(\frac{a}{a_{\text{K}}(r)}\right)^{3/2} \approx 1300 \text{ au}, \]
smaller than the transition radius \((\approx 5'\) au\), but much larger than the disk radius. Hence, the gas of the envelope would never reach the disk radius unless its angular momentum is reduced by some mechanism. We therefore believe that the relatively large, 103 au scale, centrifugal radius of the envelope is not directly associated with the formation of the much smaller rotationally supported disk. If the centrifugal radius was directly responsible for the KRD, the rotation speed inside the radius would increase toward the center and the infall speed would quickly drop to zero if the total \((\text{infall} + \text{rotation})\) kinetic energy was conserved; these are inconsistent with our observations. The significant infall speed and apparent decrease in angular momentum that we inferred in the transition region indicate the existence of a second centrifugal radius closer to the central object that is more directly responsible for the small KRD. To study it in more detail, higher resolution observations are needed.

4.2. The Keplerian Disk

The centrifugal radius of the envelope is where the centrifugal force is balanced by the gravitational force and is thus where the rotation velocity is equal to the Keplerian velocity. In our model, this radius is \( \left(\frac{v}{v_{\text{K}}}\right)^{2} r_{0} = 3.24 \text{ au} \), smaller than the transition radius \((\approx 5'\) au\), but much larger than the disk radius. Hence, the gas of the envelope would never reach the disk radius unless its angular momentum is reduced by some mechanism. We therefore believe that the relatively large, \(10^{3}\) au scale, centrifugal radius of the envelope is not directly associated with the formation of the much smaller rotationally supported disk. If the centrifugal radius was directly responsible for the KRD, the rotation speed inside the radius would increase toward the center and the infall speed would quickly drop to zero if the total \((\text{infall} + \text{rotation})\) kinetic energy was conserved; these are inconsistent with our observations. The significant infall speed and apparent decrease in angular momentum that we inferred in the transition region indicate the existence of a second centrifugal radius closer to the central object that is more directly responsible for the small KRD. To study it in more detail, higher resolution observations are needed.

Figure 5. PV diagrams in C18O (black) and SO (red) centered at the VLA 1 source, cut along the minor axis of the envelope–disk. The contour levels are the same as those in Figure 4. The gray boxes in the lower-right corners show the velocity and angular resolutions of the PV diagrams. Dashed curves show the infall velocity calculated with \( v_{i} = -1.7 \left(\frac{r}{r_{0}}\right)^{0.5} \text{ km s}^{-1} \), where \( r_{0} = 1'' \text{ (400 au)} \). Solid curves show the free-fall velocity due to the central VLA 1 source.

Figure 6. Position-angular momentum diagram in C18O centered at the VLA 1 source, derived from Figure 4(a). The specific angular momentum is derived by multiplying the rotation velocity with the distance to the VLA 1 source. The gray halftone and contour levels are the same as those in Figure 4. The asterisks and crosses also have the same meanings as those in Figure 4.
disk was reproduced well using a flat disk model with a radius of 0\textdegree 6 (e.g., 240 au). Therefore, the radius of the disk could reach up to 240 au and higher angular resolution is really needed to refine it. In Lee (2011), the gas and dust associated with the disk were estimated to have a total mass of \(\sim 0.14 \pm 0.03 \, M_\odot\). Since this mass is only \(\sim 8\%\) of the mass of the central VLA 1 source, the disk should be gravitationally stable.

### 4.3. A Ring of SO Shocks

Interestingly, SO emission is detected in the innermost part of the transition region around where the disk is formed and where the rotation velocity starts to increase again. The SO emission appears as two peaks outside the disk, one in the north where the rotation velocity starts to increase again. The SO of the transition region around where the disk is formed and needed to re

...envelope behind an ambipolar diffusion (AD) shock. The trapped flux makes the field strength in the post-AD-shock region much higher than in the pre-shock region. The strongly magnetized post-AD-shock region grows with time, reaching thousands of au in size at late times, which is larger than the 100 au scale KRD. Therefore, a generic expectation is that the KRD, where most of the remaining (after magnetic braking) angular momentum originally associated with the mass of the (single) star is stored, should be surrounded by a strongly magnetized (envelope–disk) transition region, where most of the magnetic flux originally associated with the same stellar mass is parked.

The theoretically expected, strongly magnetized, envelope–
disk transition region provides a plausible explanation for the two most puzzling features observed in the HH 111 system: (1) the large decrease of the specific angular momentum, by a factor of \(\sim 3\), from a distance of roughly 2000–160 au (see Figure 6), and (2) the slow infall outside the KRD at a speed below the free-fall value (see Figure 5). Both features can be naturally produced by a strong magnetic field, which can remove angular momentum efficiently through magnetic braking from field line twisting in the azimuthal direction, and can slow down the gravitational collapse through magnetic tension force from field pinching in the radial direction. Both of these effects have been illustrated through numerical simulations, most clearly under the assumption of axisymmetry (2D).

For example, Li et al. (2011) found that the magnetic field trapped in the post-AD-shock region could be so strong as to slow down the infall speed temporarily to less than 10\% of the local free-fall value, and remove essentially all of the angular momentum of the material passing through the region (see their Figure 5). However, exactly how much angular momentum is removed by the magnetic braking, and by how much the infall is slowed down by the magnetic forces, depend on many factors, such as the degree of core magnetization and the level of ionization. These are uncertain observationally for individual systems such as HH 111, and on model simplifications. For example, in the 3D simulations (without the axisymmetry assumption) of Krasnopolsky et al. (2012), the strongly magnetized post-AD shock region becomes unstable to the “magnetic interchange” instability, which reduces the field strength somewhat compared to the 2D case. However, the field remains strong enough to slow down the infall and to remove angular momentum so efficiently as to prevent the formation of a large, rotationally supported disk (see their Figure 5 for an illustration), at least at the relatively early times reached in their simulations. Additional physical processes, such as removal of small grains (Zhao et al. 2016) and reduction in cosmic ray ionization rate (Padovani et al. 2013), and longer simulations are needed to produce large 100 au scale disks around relatively evolved Class I sources that are more suitable for direct comparison with the observations of the HH 111 system. Nevertheless, its inferred sub-free-fall collapse and large loss of angular momentum are qualitatively consistent with the strongly magnetized envelope–disk region that is expected on general
theoretical grounds. This interpretation can be tested by future high-resolution dust polarization and Zeeman observations, perhaps with ALMA.

As for the SO shock, it could be related to the accretion shock when the infalling material right outside the KRD joins the KRD. In this case, the SO shock should be relatively thin. Alternatively, it could be related to heating through ambipolar diffusion in the post-AD-shock region, which could be broader in the radial range. The increase in rotation velocity from the innermost part of the transition region to the outer part of the KRD could be due to a redistribution of angular momentum on the disk, which tends to transport mass toward the central star and angular momentum toward the outer edge.

5. CONCLUSIONS

Our ALMA and SMA observations of the HH 111 protostellar system have shown for the first time how a Keplerian rotating disk can be formed inside a flattened envelope. As in previous study, the flattened envelope is detected in C18O, extending out to \( \gtrsim 2400 \) au from the VLA 1 source. It has a differential rotation, with the outer part (\( \gtrsim 2000 \) au) better described by a rotation that has constant specific angular momentum and the innermost part (\( \lesssim 160 \) au) by a Keplerian rotation. The rotationally supported disk is therefore relatively compact in this system, which is consistent with the dust continuum observations. Most interestingly, there is a substantial drop in specific angular momentum in the envelope–disk transition region from 2000 to 160 au, by a factor of \( \sim 3 \), if the flow to the protostar is assumed to be in the steady state. Such a decrease is not expected outside a disk formed from simple hydrodynamic core collapse, but can happen naturally if the core is significantly magnetized, because magnetic fields can be trapped in the transition region outside the disk by the ram pressure of the protostellar accretion flow, which can lead to efficient magnetic braking. In addition, SO shock emission is detected around the outer radius of the disk and could trace an accretion shock around the disk.

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