ALMA Observations of the Very Young Class 0 Protostellar System HH211-mms: A 30 au Dusty Disk with a Disk Wind Traced by SO?

Chin-Fei Lee1,2, Zhi-Yun Li3, Naomi Hirano1, Hsien Shang1, Paul T. P. Ho1,4, and Qizhou Zhang5

1 Academia Sinica Institute of Astronomy and Astrophysics, P.O. Box 23-141, Taipei 106, Taiwan; cfelee@asiaa.sinica.edu.tw
2 Graduate Institute of Astronomy and Astrophysics, National Taiwan University, No. 1, Sec. 4, Roosevelt Road, Taipei 10617, Taiwan
3 Astronomy Department, University of Virginia, Charlottesville, VA 22904, USA
4 East Asian Observatory, 660 N. A’ohoku Place, University Park, Hilo, HI 96720, USA
5 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

Received 2018 May 1; revised 2018 July 9; accepted 2018 July 9; published 2018 August 1

Abstract

HH 211-mms is one of the youngest Class 0 protostellar systems in Perseus, at a distance of ∼235 pc. We have mapped its central region at up to ∼7 au (0″03 resolution). A dusty disk is seen deeply embedded in a flattened envelope, with an intensity jump in the dust continuum at ∼350 GHz. It is nearly edge-on and is almost exactly perpendicular to the jet axis. It has a size of ∼30 au along the major axis. It is geometrically thick, indicating that the (sub)millimeter light-emitting grains have yet to settle to the midplane. Its inner part is expected to have transformed into a Keplerian rotating disk with a radius of ∼10 au. A rotating disk atmosphere and a compact rotating bipolar outflow are detected in SO N2H+ = 8_8. The outflow fans out from the inner disk surfaces and is rotating in the same direction as the flattened envelope, and hence could trace a disk wind carrying away angular momentum from the inner disk. From the rotation of the disk atmosphere, the protostellar mass is estimated to be <50 M_Jup. Together with results from the literature, our result favors a model where the disk radius grows linearly with the protostellar mass, as predicted by models of pre-stellar dense core evolution that asymptote to an r−1 radial profile for both the column density and angular velocity.

Key words: accretion, accretion disks – ISM: individual (HH 211) – ISM: jets and outflows – stars: formation

1. Introduction

In the earliest phase of star formation, the magnetic field may remove angular momentum in a collapsing core efficiently through magnetic braking, potentially preventing a Keplerian rotating disk from forming around a protostar (Allen et al. 2003; Mellon & Li 2008). However, since Keplerian disks have been detected as early as in the Class 0 phase, it is unclear how efficiently the magnetic braking can actually remove the angular momentum. In particular, a few Class 0 protostellar systems, e.g., VLA 1623 (Murillo et al. 2013), L1527 (Sakai et al. 2014), and HH 212 (Lee et al. 2017a, 2017b), have been found to harbor Keplerian disks. Here, by mapping the much younger system HH 211-mms with the Atacama Large Millimeter/submillimeter Array (ALMA), we aim to determine how early and how small a disk can form in order to provide stronger constraints on current models of disk formation. In addition, by comparing our disk result to those in the literature, we can also study the disk growth in the earliest phase of star formation.

It is still unclear how angular momentum can be partly removed from a disk in order for the disk material to transport from the outer to the inner part. One possible mechanism is through a low-velocity extended tenuous disk wind (Konigl & Pudritz 2000). Rotating molecular outflows have been detected extending out from the disks in a few protostellar systems (Launhardt et al. 2009; Agra-Amboage et al. 2011; Greenhill et al. 2013; Bjerkeli et al. 2016; Hirota et al. 2017; Tabone et al. 2017; Lee et al. 2018). If those outflows really trace the disk winds that facilitate the disk evolution, we expect to detect a rotating molecular outflow in HH 211-mms as well.

HH 211-mms is a very young and very low-mass Class 0 protostellar system in Perseus (Gueth & Guilloteau 1999; Froebrich et al. 2003; Rebull et al. 2007; Lee et al. 2009, 2010), located at a distance of ∼235 pc (Hirota et al. 2008). It was not detected at 24 μm with Spitzer (Rebull et al. 2007) and thus appears to be very similar to the PACS Bright Red Sources (Stutz et al. 2013), which seem to be among the youngest protostars in Orion. Therefore, it appears to be among the youngest Class 0 protostars in Perseus. A collimated jet and a collimated outflow are observed associated with the central protostar (McCaughean et al. 1994; Gueth & Guilloteau 1999; Hirano et al. 2006; Palau et al. 2006; Lee et al. 2007). Based on current jet-launching models, a Keplerian disk is required to launch the jet. Recent observations with the Karl G. Jansky Very Large Array (VLA) have also shown a marginally resolved disk with a deconvolved size of ∼22 au at 36.9 GHz at ~16 au (0″07) resolution (Segura-Cox et al. 2016). In this paper, we zoom in to the innermost region of this system with ALMA at up to 7 au (0″03) resolution at 350 GHz. We not only confirm the presence of the disk but also spatially resolve it in the dust continuum along the major and minor axes. We also detect a rotating disk atmosphere and a compact rotating molecular outflow in SO. We will discuss the disk formation and check whether the rotating outflow can trace a disk wind. We will also discuss how rapidly a disk can grow by comparing our result to those in the literature.

2. Observations

We have mapped HH 211-mms (Project ID: 2015.1.00024.S) with ALMA at ∼350 GHz in Band 7, with one pointing toward the center. As shown in Table 1, a C36-7 array configuration was used with 37–41 antennas. Four executions were carried out in 2015 in Cycle 3, one on December 4, one on December 5, and two on December 6. The execution on December 5 was excluded because of its poor phase stability due to high water vapor column density. The projected baselines were 15–7930 m.
Table 1  
Observation Logs

| Cycle | Date       | Array Configuration | Number of Antennas | Time on Target (min) | Projected Baselines (m) |
|-------|------------|---------------------|--------------------|----------------------|-------------------------|
| 3     | 2015 Dec 4 | C36-7               | 37                 | 41                   | 16–7930                 |
| 3     | 2015 Dec 5 | C36-7               | 41                 | 41                   | 13–5800                 |
| 3     | 2015 Dec 6 | C36-7               | 37                 | 41                   | 15–6200                 |
| 3     | 2015 Dec 6 | C36-7               | 37                 | 41                   | 35–5890                 |

The resulting maximum recoverable scale was ~0″4. As shown in Table 2, we had six spectral windows in the correlator setup, with five for molecular lines at a velocity resolution of ~0.212 km s\(^{-1}\) per channel and one for the continuum (with possible weak lines) at a velocity resolution of ~0.848 km s\(^{-1}\) per channel. The total usable time on HH 211-mms was ~123 min.

The CASA package was used to calibrate the data. The bandpass, flux, and phase calibrators are listed in Table 3 with their flux densities. Although there was a jump in the flux density of the flux calibrator from 2015 December 4 to 2015 December 5, the resulting flux densities of the phase calibrator are the same and the resulting flux densities of HH 211-mms are consistent to within ~10%. Here, we only present the results in the continuum and SO, with the continuum tracing the dusty disk and SO tracing the disk atmosphere and rotating bipolar outflow. Previously, the HCO\(^+\) line was thought to trace a disk (Lee et al. 2009). However, here at high resolution, we see that it suffers from an absorption against the disk continuum and thus no emission is detected toward the disk, as seen in HH 212 (Lee et al. 2017b). Therefore, the HCO\(^+\) line can only trace the flattened envelope around the disk and thus will be reported in the near future. No clear H\(^{13}\)CO\(^+\) line is detected. SiO and CO lines trace the jet and will also be reported in the near future.

Line-free channels were combined to produce the continuum channels. Robust weighting factors of 0.5 and ~0.5 were used for the visibility to generate the continuum maps at ~0″047 × 0″031 resolution with a noise level of 0.11 mJy beam\(^{-1}\) (or 0.73 K) and 0″036 × 0″024 resolution with a noise level of 0.154 mJy beam\(^{-1}\) (or 1.75 K). On the other hand, since SO emission is weak, a robust weighting factor of 2 was used for the visibility to generate the SO maps at ~0″064 × 0″046 resolution. To achieve a better detection, we binned the channel maps with a velocity resolution of 3 km s\(^{-1}\) and a noise level of ~1.6 mJy beam\(^{-1}\) (or 5.6 K). In the channel maps, the velocities are in the LSR system.

3. Results

In HH 211-mms, the systemic velocity is \(V_{\text{sys}} = 9.2 \pm 0.1\) km s\(^{-1}\) LSR, as derived from the optically thin line of H\(^{13}\)CO\(^+\) toward the system (Gueth & Guilloteau 1999). Throughout this paper, an offset velocity \(V_{\text{off}} = V_{\text{LSR}} - V_{\text{sys}}\) is defined to simplify our presentations. In this system, the jet has a position angle of 116°5 and an inclination angle of ≤6° to the plane of the sky, with the southeastern (SE) component tilted toward us (Gueth & Guilloteau 1999; Lee et al. 2009; Jhan & Lee 2016).

3.1. Disk in the Continuum at 350 GHz

Figure 1(a) shows the continuum map toward the central region at a frequency of ~350 GHz and resolution of ~0″04. A compact and bright disklike structure is seen inside an extended and faint envelope that is elongated roughly perpendicular to the jet axis. The envelope and disk have a total flux density of ~192 ± 38 mJy, measured within the 5σ contour. Notice that, unlike the previous continuum map shown at ~0″2 resolution in Lee et al. (2009), no secondary emission peak is seen here at ~0″3 toward the southwest (SW). In order to confirm this, we made a continuum map with a similar resolution to that in Lee et al. (2009) using a taper of 0″25, but still only observed a smooth extension of the envelope toward the SW to ~0″4. Thus, the secondary emission peak seen in Lee et al. (2009) is likely an artifact due to limited UV-coverages of the Submillimeter Array when using the super-uniform weighting on the visibilities. Zooming into the center at a higher resolution of ~0″03, we can better resolve the disk structure, as shown in Figure 1(b). Notice that the envelope becomes mostly below 3σ detection due to the higher noise level in brightness temperature at higher resolution. The disk has an emission peak at the position \(\alpha(2000) = 3^\text{h}43^\text{m}56^\text{s}0545\) and \(\delta(2000) = 32^\circ00'50''189\), which is considered to be the location of the central protostar in this paper. The disk has a total flux density of ~83 ± 16 mJy, measured within the ~5σ contour.

A two-dimensional Gaussian fit to the disk structure indicates that the disk has a major axis at a position angle of 27°6 and is thus almost exactly perpendicular to the jet axis. This, together with the known jet orientation, suggests that the disk is close to edge-on, with an inclination angle of ≤6° to the plane of the sky (here 0° for an edge-on disk) and the nearside tilted to the northwest (NW). The disk has a deconvolved size (FWHM) of 0″127 (or ≈30 au) along the major axis and 0″067 (~16 au) along the minor axis. The aspect ratio of the disk in the plane of the sky is ~0.5, larger than that expected for a thin disk with an inclination angle of 6°, which is ~0.1. Therefore, the disk is geometrically thick, as found in the slightly evolved but vertically resolved edge-on Class 0 disks, e.g., HH 212 (Lee et al. 2017a). This indicates that the (sub)millimeter-light-emitting grains have yet to settle to the midplane. This is different from the Class I disk HH 30, which is very thin in the dust continuum image (unresolved vertically; F. Menard et al. 2018, in preparation), or the Class I/II disk HL Tau, which has signs of dust settling from the shape of the gaps (ALMA Partnership et al. 2015). Observations at higher resolution are needed to check in HH 211-mms for a dark lane similar to that seen in HH 212 (Lee et al. 2017a).

An intensity cut along the major axis of the disk shows an intensity jump at the position offsets of ~±0″1 from ~10 K there to ~90 K at the source position (Figure 1(c)). These position offsets can be considered as the locations where the innermost envelope transitions to the disk, as discussed in HH 212 (Lee et al. 2017a, 2017b). The intensity profile has a FWHM of ~0″134, resulting in a deconvolved FWHM of 0″127 along the major axis, as found earlier in the two-dimensional Gaussian fit to the disk structure.

We can study the disk properties by estimating the spectral index \(\alpha\) (with the flux density \(F_\nu \propto \nu^\alpha\)) in the spectral energy distribution of the disk emission, using the flux densities of the disk emission at two different frequencies. Previously, the disk has been detected by the VLA at 36.9 GHz at a resolution of ~0″07 with a flux density of ~0.855 mJy (Segura-Cox et al. 2016;
Tobin et al. 2016). Part of this flux density is believed to be from free–free emission, because the spectral index between 36.9 and 28.5 GHz is ~1.65 (Tobin et al. 2016). Recent analysis shows that the dust emission corrected for the free–free emission is ~0.57 mJy at ~33 GHz (λ ~ 9 mm) in Ka-band observations (Tychoniec et al. 2018). Therefore, with the flux density of the disk measured above at 350 GHz, we have α ~ 2.11 ± 0.2, slightly higher than that for an optically thick thermal dust emission, for which α = 2. Thus, the disk here must be warm and partly optically thick.

Assuming that the disk emission is optically thin, the (gas and dust) mass of the disk can be roughly estimated using the formula

$$M_{\text{disk}} \sim \frac{D^2F_a}{B_{\nu}(T_{\text{dust}})\kappa_{\nu}}$$  

(1)

where $D$ is the distance to the source, $B_{\nu}$ is the blackbody intensity at the dust temperature $T_{\text{dust}}$, $F_a$ is the observed flux density, and $\kappa_{\nu}$ is the mass opacity per gram of gas and dust mass. As discussed earlier, the observed brightness temperature reaches 90 K, thus we assume $T_{\text{dust}} = 100$ K. Since the mass opacity is uncertain, we assume two different mass opacities for two different phases of star formation. One is the empirical opacity derived from T-Tauri disks in the late phase of star formation, which is $\kappa_{\nu} = 0.1(\nu/10^3 \text{GHz})^{3} \text{cm}^2 \text{g}^{-1}$ (Beckwith et al. 1990), and the other is the mass opacity of protostellar cores in the early phase (Ossenkopf & Henning 1994), which is $\kappa_{\nu} = 0.00899(\nu/231 \text{GHz})^{3} \text{cm}^2 \text{g}^{-1}$ (Tychoniec et al. 2018), where $\beta$ is the dust opacity index. The actual opacity of the HH 211 protostellar disk can be in between the two. We assume $\beta = 1$, as usually assumed for protostellar disks (Andrews et al. 2009). The resulting disk masses are ~1.8 $M_{\text{Jup}}$ and ~4.6 $M_{\text{Jup}}$, respectively. Since the emission is at least partially optically thick, the masses estimated here are only lower limits.

We can compare the disk masses estimated above with that derived from the emission at 33 GHz, which is more optically thin. At that frequency, the mass opacity is an extrapolation of...
from the above mass opacities (which were derived for the wavelength $\lambda \lesssim 1.3$ mm) and is thus more uncertain. Adopting a flux density of $0.57$ mJy at $33$ GHz (Tychoniec et al. 2018), the resulting disk masses are $\sim 14 M_{Jup}$ and $35 M_{Jup}$ respectively, for the two different mass opacities, and thus are much higher than those estimated above. Previously with the same formula, Tychoniec et al. (2018) has derived a disk mass of $\sim 120 M_{Jup}$, assuming a dust temperature of $30$ K and a mass opacity of protostellar cores. As discussed above, a dust temperature of $\sim 100$ K is more reasonable. Thus the disk mass should be revised to be $\sim 35 M_{Jup}$. Since the mass opacity is so uncertain and the continuum at lower frequency can probe further in where the temperature is higher, further work is needed to check the disk masses derived here at $33$ GHz.

3.2. Disk Atmosphere and Rotating Outflow in SO

SO $N_J = 8_g - 7_e$ emission is detected within $\sim 0''13$ (30 au) of the central source, as shown in Figure 2(a). It traces a compact bipolar outflow, consisting of a SE component and a NW component, extending out from the disk surfaces surrounding the jet axis. The outflow width reaches $\sim 0''2$ (46 au) at a height of $\sim 0''1$ (23 au). Note that faint SO emission is also detected along the jet axis at a distance $>1''$ from the central source, tracing the knots in the jet as seen before in Lee et al. (2010), but it is too faint to be discussed here meaningfully. Almost no SO emission is detected along the major axis of the dusty disk, likely because the dust emission there is optically thick and bright, as seen in HH 212 (Lee et al. 2017b). As shown in Figure 2(b), the spectrum averaged over the emitting region shows that most emission is within $\sim \pm 10$ km s$^{-1}$ of the systemic velocity. The spectrum profile is asymmetric about the systemic velocity, with less emission in the blue.

The structure of the SO emission can be better seen in the channel maps shown in Figure 3. The SE and NW outflow components are seen in both redshifted and blueshifted velocities, with the SE component extending to higher blueshifted velocities and the NW component extending to higher redshifted velocities. This is expected because the outflow must have similar inclination to the jet and is thus almost in the plane of the sky, with the SE component tilted slightly toward us and the NW component tilted slightly away from us. At low velocities with $|V_{off}| \lesssim 4.5$ km s$^{-1}$, the SO emission on the dusty disk surfaces forms flattened structures aligned with the dusty disk surfaces (see Figures 3(c)–(f)), and thus actually traces the disk atmosphere, as seen in HH 212. The disk atmosphere can be clearly seen at the lowest velocities, as indicated in Figures 3(d) and (e), with its radius estimated to be $\sim 0''05$ or 12 au, using a $4\sigma$ detection level. Above the disk surfaces, the SO emission forms shell-like structures around the jet axis opening to the SE and NW from the inner disk (see Figures 3(c)–(f)), tracing the outflow shells. Going from the blueshifted to redshifted velocity, the emission of the shell moves from the SW to the northeast (NE) of the jet axis. This velocity sense is the same as that seen before in the HCO$^+$ rotating flattened envelope (Lee et al. 2009), implying that the shell is rotating with the same velocity sense as the flattened envelope. At higher velocity with $|V_{off}| > 4.5$ km s$^{-1}$, the emission is seen along the jet axis, probably tracing the front and back walls of the outflow shells projected along the jet axis.

Figure 4 shows the position–velocity (PV) diagrams across the jet axis at increasing distance from the central source. The kinematics of the disk atmosphere can be studied with the PV diagrams at the disk surfaces in Figures 4(a) and (d). As mentioned above, the disk atmosphere is traced by the emission on the disk surfaces with $|V_{off}| \lesssim 4.5$ km s$^{-1}$. There the redshifted emission is seen in the NE and the blueshifted in the SW (see Figures 4(a) and (d), the same as those seen in the HCO$^+$ rotating flattened envelope. Notice that in Figure 4(d), the emission at $V_{off} \sim -0.5$ km s$^{-1}$ and $0''12$ is a separate component not associated with the disk atmosphere in the NW, and further observations are needed to determine its origin. In addition, the outer boundaries of the PV structures can be roughly outlined by the magenta curves, which are the Keplerian rotation curves due to a protostellar mass of $50 M_{Jup}$, suggesting that the central protostar has a mass of...
For the disk atmosphere in the SE, a linear PV structure (as delineated by the green line in Figure 4(a)) is seen, revealing a rotating ring in the atmosphere. For the disk atmosphere in the NW, a roughly elliptical-like PV structure (as delineated by the tilted green ellipse in Figure 4(d)) can be seen, revealing a rotating and expanding ring in the atmosphere. This indicates that the atmosphere there has been significantly affected by the outflow, as seen in HH 212 (Lee et al. 2018). Notice that the center of the PV structure (bracketed by the Keplerian curves) has a velocity shift of $\sim-0.5 \text{ km s}^{-1}$ in the SE atmosphere and $\sim0.5 \text{ km s}^{-1}$ in the NW atmosphere. This implies that the atmosphere also has a small outflow velocity of $\sim5 \text{ km s}^{-1}$, assuming an inclination angle of $6^\circ$. However, since the velocity shift is small, further observations are needed to confirm the outflow velocity of the atmosphere.

The kinematics of the bipolar rotating outflow can be studied with the PV diagrams above the disk surfaces in Figures 4(b)–(c) and (e)–(f). For the SE outflow component, the blueshifted and redshifted emission are seen on the opposite sides of the jet axis (Figures 4(b) and (c)), as discussed above. The specific angular momentum of the outflow is estimated to be $\lesssim20 \text{ au km s}^{-1}$, with the largest possible value marked by the linear line in the diagrams. For the NW outflow component (Figures 4(e) and (f)), as shown by the tilted green ellipse, the emission structure could form a tilted elliptical PV structure, as seen before in the rotating outflow in Orion BN/KL Source I (Hirota et al. 2017) and HH 212 (Lee et al. 2018). From these elliptical PV structures, we estimated a similar specific angular momentum of $\sim20 \text{ au km s}^{-1}$, with an expansion velocity of 6–7 km s$^{-1}$. On the other hand, we cannot identify any elliptical PV structure in Figures 4(b) and (c), and hence cannot estimate the expansion velocity for the SE outflow component.

Figure 5 shows the PV diagram cut along the jet axis. Most of the emission is associated with the disk atmosphere with position offsets of $\sim\pm0.06$. Not much emission is seen from the outflow along the jet axis. Future observations are needed to resolve the PV structure of the disk atmosphere along the jet axis.

As seen in Figure 2(a), the SO emission has a mean intensity of $300 \pm 60 \text{ K km s}^{-1}$. Assuming an optically thin emission in local thermodynamic equilibrium and an excitation temperature of $\sim100 \text{ K}$ as in HH 212 (Lee et al. 2018), the mean SO
The column density is estimated to be $\sim 4.4 \pm 0.9 \times 10^{15} \text{ cm}^{-2}$. Assuming an SO abundance of $2 \times 10^{-6}$ as found in the jet (Lee et al. 2010), the molecular hydrogen column density is $\sim 2.2 \pm 0.4 \times 10^{21} \text{ cm}^{-2}$. This SO abundance in the jet was derived previously by dividing the SO column density by the $\text{H}_2$ column density (derived from CO emission) in the jet (Lee et al. 2010). Given that the shell thickness is $\lesssim 0.05$ or $12 \text{ au}$, the mean density in the shell is $\gtrsim 1.2 \times 10^7 \text{ cm}^{-3}$, which is close to the critical density of the SO line. The total flux of the SO emission is $\sim 0.87 \text{ Jy km s}^{-1}$. Thus, the total mass in the atmosphere and rotating outflow is $\sim 1.3 \times 10^{-3} \text{ M}_\text{Jup}$.

4. Discussion

4.1. Disk Growth and Magnetic Braking

In some early models of magnetized core collapse, magnetic braking can prevent a Keplerian rotating disk from forming around a central protostar in the earliest phase of star formation (e.g., Allen et al. 2003; Mellon & Li 2008). However, recent works have shown that, in addition to misaligned magnetic fields (Hennebelle & Ciardi 2009), non-ideal magneto-hydrodynamic effects, e.g., Ohmic dissipation and ambipolar diffusion, can enable formation of Keplerian rotating disks (Dapp & Basu 2010; Machida & Matsumoto 2011; Masson et al. 2016; Zhao et al. 2018). Recent ALMA observations at unprecedented angular resolution have also shown that a
Keplerian disk can form in $\sim 5 \times 10^4$ yr old Class 0 system HH 212 (Lee et al. 2017a, 2017b). In that system, a dusty disk with a radius of $\sim 60$ au is detected with an intensity jump of $\sim 10$ from the envelope to the disk in the continuum emission at 350 GHz. This intensity jump is believed to trace a density jump produced by an accretion shock around the disk and the envelope transforms to a Keplerian disk after passing through the shock. Indeed, a Keplerian disk with a smaller radius of $\sim 44$ au, which is about two-thirds of the dusty disk radius, was subsequently confirmed from a kinematic study in molecular lines (Lee et al. 2017b).

HH 211-mms is younger than HH 212. Interestingly, a similar intensity jump of $\sim 9$ is also seen in the continuum emission at 350 GHz at a radius of $\sim 15$ au (see Section 3.2). Since this intensity jump can also trace a density jump produced by an accretion shock, a Keplerian disk might have formed with a smaller radius of $\sim 10$ au, roughly in agreement with the radius of the rotating disk atmosphere detected in SO. A similar disk radius was also estimated at 36.9 GHz (or 8.1 mm) (Segura-Cox et al. 2016). In this system, the rotation axis of the disk must be aligned with the jet axis, because the disk is almost exactly perpendicular to the jet. Since the magnetic field in the cloud core is mostly N–S oriented (Matthews et al. 2009; Hull et al. 2014), a large misalignment of $\sim 60^\circ$ exists between the magnetic field axis in the cloud core and the rotation axis of the disk. Hence, it is possible that the magnetic braking here is not efficient enough to prevent a disk from forming. Previous dust polarization observations toward the inner envelope of HH 211-mms showed a hint of a toroidal magnetic field wrapping around the disk, further supporting this possibility (Lee et al. 2014). The disk here is small, likely because the specific angular momentum in the envelope is small, roughly estimated to be $\sim 35$ au km s$^{-1}$ from the HCO$^+$ envelope in Lee et al. (2009). This value is much smaller than that in HH 212, which is $\sim 140$ au km s$^{-1}$, and L1527 (54 au disk), which is $\sim 130$ au km s$^{-1}$ (Ohashi et al. 2014).

In addition, HH 211-mms is much younger than HH 212 and L1527, and thus it is likely that only the inner cloud core with smaller angular momentum has collapsed into the center. As discussed in Tanner & Arce (2011), the radius of the dynamical collapse in HH 211-mms could be only $\sim 870$ au, adjusted to the new distance of 235 pc. As shown in their Figure 11, this is the radius where the specific angular momentum of the extended ammonia envelope decreases to roughly the same as that of the inner HCO$^+$ envelope.

The growth of Keplerian disk radius from Class 0 to I phase has been studied by Yen et al. (2017). Figure 6 shows their plot after adding our measurement of HH 211-mms and the new measurement of HH 212 in Lee et al. (2017b). Previously, the trend of the disk growth with the protostellar mass in the early Class 0 phase could not be determined because no disk measurement was confirmed for the protostellar mass less than 0.2 $M_\odot$. In particular, the two small disk radii with protostellar mass $<0.04$ $M_\odot$ (the two leftmost open squares) were inferred from the observations at a resolution of $\sim 100$ au and thus are quite uncertain. For B335, which has a protostellar mass of $\lesssim 0.05$ $M_\odot$, a disk radius of $\sim 3$ au was inferred from an observation at $\sim 50$ au resolution, and thus is also very uncertain. In addition, the very small disk radius of B335 could result from magnetic braking (Yen et al. 2015). Now with our measurement of HH 211-mms, we can see more clearly that the disk radius is large enough to be measured with a current instrument (ALMA) in the earliest phase of star formation. The significance of this radius measurement can be gauged from Figure 6, where we present the expectations for two competing scenarios of protostellar disk growth. The first is based on the classic picture of Terebey et al. (1984), who considered the growth of a disk in the collapse of a singular isothermal sphere (SIS) with a solid-body rotation. In this case, the disk radius stays small initially, but grows rapidly with stellar mass at later times, as $R_d \propto M_\star^3$. The reason for such a steep dependence is that the materials at small radii of the SIS rotate very slowly and, when they collapse, they form a very small disk initially. The disk size grows rapidly at later times, as the materials at larger radii of the SIS with much larger specific angular momenta collapse to the central region. The coefficient in front of the $M_\star^3$ scaling depends on the isothermal sound speed and especially the initial rotation rate of the SIS, which is uncertain. In Figure 6, there are two dashed cyan lines for two coefficients chosen to roughly bracket the currently available data on late Class 0 and early Class I sources. Extension of these lines to earlier times when the protostellar mass is smaller represents the expectation of this “slow-start, rapid-growth” scenario for the youngest Class 0 disks based on the current data. The upper limit inferred for the disk radius for B335 and the lower limit inferred for its stellar mass appear to provide some support for this scenario. However, this support is rather weak, because the disk in B335 has never been detected. Without detecting the disk, it would be difficult to infer the stellar mass or put a strong upper limit on it.

An alternative scaling was advocated by Basu (1998), based on the asymptotic state of the pre-stellar evolution of a rotating, magnetized dense core, which is expected to have a power-law distribution for both the column density $\Sigma \propto r^{-1}$ and the angular speed $\Omega \propto r^{-1}$ right before the formation of a central stellar object. Compared to the SIS rotating as a solid body in the first scenario, the materials at small radii rotate much faster; they collapse to form a much larger disk compared to the first scenario. Such a disk grows more slowly with the stellar mass at later times, as $R_d \propto M_\star$, because the specific angular momentum in the pre-collapse configuration increases with radius more slowly compared to the first scenario. The coefficient of the linear scaling depends on the sound speed, magnetic field strength, and the rotation rate, and can be different for different sources. In Figure 6, two (green) dotted lines with different coefficients are plotted to roughly bracket the current data for the late Class 0 and early Class I sources. Extension of these lines to earlier times represents the expectation of this “early-start, slow-growth” scenario for the youngest Class 0 disks. Our measurement of the radius of HH 211-mms disk and estimate for its mass lie in the expected region, which provides support for this scenario; they are not consistent with the expectation of the “slow-start, rapid-growth” scenario based on Terebey et al. (1984). Indeed, the trend of linear growth of disk radius with protostellar mass appears to extend to the late Class I phase. However, the disk growth in this phase could be modified by magnetic braking, as suggested by our previous observation of HH 111 (Lee et al. 2016).

4.2. Disk Atmosphere and Disk Wind?

In SO, a disk rotating atmosphere is seen on the dusty disk surfaces and a bipolar rotating molecular outflow is seen coming out
We have confirmed the presence of a disk in HH 211-mms with ALMA at up to ~7 au resolution. The disk is seen inside a flattened envelope with an intensity jump in the dust continuum at ~350 GHz. It is nearly edge-on and is almost exactly perpendicular to the jet axis. It has a size of ~30 au along the major axis and ~16 au along the minor axis. It is geometrically thick, indicating that the (sub)millimeter light-emitting grains have yet to settle to the midplane. Its inner part is expected to have transformed into a Keplerian rotating disk with a radius of ~10 au. Thus, a Keplerian disk can form around protostars with a radius as small as ~10 au. Our result for HH 211-mms favors a model where the disk size grows linearly with protostellar mass $M_*$ rather than with $M_*^{2/3}$. In addition, we have detected a disk atmosphere and a compact rotating bipolar outflow in SO $N_J = 8g - 7g$. The disk atmosphere is rotating and has a small outflow velocity of a few km s$^{-1}$ in the outflow direction. It is also expanding and could be affected by the outflow. The outflow extends out to ~30 au from the disk surfaces to the SE and NW around the jet axis. It is rotating in the same direction as the flattened envelope, and hence could trace a wind carrying away angular momentum from the inner disk.

We thank the referee for the constructive comments on our paper. This paper makes use of the following ALMA data: ADS/JAO.ALMA#2015.1.00024.S. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada), NSC and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ. C.-F.L. acknowledges grants from the Ministry of Science and Technology of Taiwan (MoST 104-2119-M-001-015-MY3) and the Academia Sinica (Career Development Award). Z.Y.L. is supported in part by NSF grant AST-1313083 and AST-1716259 and NASA grant NNX14AB38G.

ORCID iDs

Chin-Fei Lee https://orcid.org/0000-0002-3024-5864

References

Agra-Amboage, V., Dougdoss, C., Cabrit, S., & Reunanen, J. 2011, A&A, 532, A59
Allen, A., Li, Z., & Shu, F. H. 2003, ApJ, 599, 363
ALMA Partnership, Brogan, C. L., Pérez, L. M., et al. 2015, ApJL, 808, L3
Andrews, S. M., Wilner, D. J., Hughes, A. M., Qi, C., & Dullemond, C. P. 2009, ApJ, 700, 1502
Basu, S. 1998, ApJ, 509, 229
Beckwit, S. W., Varghese, A. J., Chini, R. S., & Guesten, R. 1990, AJ, 99, 924
Bjerkeli, P., van der Wiel, M. H. D., Harsono, D., Ramsey, J. P., & Jørgensen, J. K. 2016, Natur, 540, 406
Dapp, W. B., & Basu, S. 2010, A&A, 521, L56
Froebrich, D., Smith, M. D., Hodapp, K.-W., & Eisloeffel, J. 2003, MNARS, 346, 163
Greenhill, L. J., Goddi, C., Chandler, C. J., Matthews, L. D., & Humphreys, E. M. L. 2013, ApJL, 770, L32
Gueth, F., & Guilloteau, S. 1999, A&A, 343, 571
Hennebelle, P., & Ciardi, A. 2009, A&A, 506, L29
Hirano, N., Liseau, R., Shang, H., et al. 2003, ApJ, 599, 1502
Hirota, T., Bushimata, T., Choi, Y. K., et al. 2008, PASJ, 60, 37
Hirota, T., Machida, M. N., Matsushita, Y., et al. 2017, NatAs, 1, 0146
Hull, C. E. H., Plambeck, R. L., Kwon, W., et al. 2014, ApJS, 213, 13
Jhan, K.-S., & Lee, C.-F. 2016, ApJ, 816, 32
Konigl, A., & Pudritz, R. E. 2000, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Tucson, AZ: Univ. Arizona Press), 759
Launhardt, R., Pavlyuchenkov, Y., Gueth, F., et al. 2009, A&A, 494, 147
Lee, C.-F., Hasegawa, T. I., Hirota, N., et al. 2010, ApJ, 713, 731
Lee, C.-F., Hirano, N., Palau, A., et al. 2009, ApJ, 699, 1584
Lee, C.-F., Ho, P. T. P., Hirano, N., et al. 2007, ApJ, 659, 499
Lee, C.-F., Hwang, H.-C., & Li, Z.-Y. 2016, ApJ, 826, 213
Lee, C.-F., Li, Z.-Y., Codella, C., et al. 2018, ApJ, 856, 14
Lee, C.-F., Li, Z.-Y., Ho, P. T. P., et al. 2017a, SciA, 3, e1602935
Lee, C.-F., Li, Z.-Y., Ho, P. T. P., et al. 2017b, ApJ, 845, 27
Lee, C.-F., Rao, R., Ching, T.-C., et al. 2014, ApJ, 797, L9
Machida, M. N., & Matsuyama, T. 2011, MNARS, 415, 2767

Figure 6. Protostellar mass vs. disk radius, adapted from Figure 10 in Yen et al. (2017) after adding our measurement of HH 211-mms and the new measurement of HH 212 in Lee et al. (2017b). Red boxes, either filled or open, are for Class 0 sources. The open boxes indicate the values inferred from unresolved observations, representing the upper limits. Blue boxes are for Class I sources. As in Yen et al. (2017), two possible trends of disk growth are plotted, one with green dashed lines for $R_d \propto M_*$, the other with cyan dashed lines for $R_d \propto M_*^{3/2}$. The Astrophysical Journal, 863:94 (9pp), 2018 August 10
Masson, J., Chabrier, G., Hennebelle, P., Vaytet, N., & Commerçon, B. 2016, 
A&A, 587, A32
Matthews, B. C., McPhee, C. A., Fissel, L. M., & Curran, R. L. 2009, ApJS, 
182, 143
McCaughrean, M. J., Rayner, J. T., & Zinnecker, H. 1994, ApJL, 436, L189
Mellon, R. R., & Li, Z.-Y. 2008, ApJ, 681, 1356
Murillo, N. M., Lai, S.-P., Bruderer, S., Harsono, D., & van Dishoeck, E. F. 
2013, A&A, 560, A103
Ohashi, N., Saigo, K., Aso, Y., et al. 2014, ApJ, 796, 131
Ossenkopf, V., & Henning, T. 1994, A&A, 291, 943
Palau, A., Ho, P. T. P., Zhang, Q., et al. 2006, ApJL, 636, L137
Rebull, L. M., Stapelfeldt, K. R., Evans, N. J., II, et al. 2007, ApJS, 171, 447
Sakai, N., Oya, Y., Higuchi, A. E., et al. 2017, MNRAS, 467, L76
Sakai, N., Sakai, T., Hiroya, T., et al. 2014, Natur, 507, 78
Segura-Cox, D. M., Harris, R. J., Tobin, J. J., et al. 2016, ApJL, 817, L14
Stutz, A. M., Tobin, J. J., Stanke, T., et al. 2013, ApJ, 767, 36
Tabone, B., Cabrit, S., Bianchi, E., et al. 2017, A&A, 607, L6
Tanner, J. D., & Arce, H. G. 2011, ApJ, 726, 40
Terebey, S., Shu, F. H., & Cassen, P. 1984, ApJ, 286, 529
Tobin, J. J., Looney, L. W., Li, Z.-Y., et al. 2016, ApJ, 818, 73
Tychoniec, Ł., Tobin, J. J., Karska, A., et al. 2018, in press
Yen, H.-W., Koch, P. M., Takakuwa, S., et al. 2017, ApJ, 834, 178
Yen, H.-W., Takakuwa, S., Koch, P. M., et al. 2015, ApJ, 812, 129
Zhao, B., Caselli, P., Li, Z.-Y., & Krasnopolsky, R. 2018, MNRAS, 473, 4868

The Astrophysical Journal, 863:94 (9pp), 2018 August 10
Lee et al.