Formation and Atmosphere of Complex Organic Molecules of the HH 212 Protostellar Disk

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Abstract

HH 212 is a nearby (400 pc) Class 0 protostellar system recently found to host a “hamburger”-shaped dusty disk with a radius of ∼60 au, deeply embedded in an infalling-rotating flattened envelope. We have spatially resolved this envelope-disk system with the Atacama Large Millimeter/submillimeter Array at up to ∼16 au (0″04) resolution. The envelope is detected in HCO+ J = 4–3 down to the dusty disk. Complex organic molecules (COMs) and doubly deuterated formaldehyde (D2CO) are detected above and below the dusty disk within ∼40 au of the central protostar. The COMs are methanol (CH3OH), deuterated methanol (CH3DOH), methyl mercaptan (CH3SH), and formamide (NH2CHO, a prebiotic precursor). We have modeled the gas kinematics in HCO+ and COMs and found a centrifugal barrier (CB) at a radius of ∼44 au, within which a Keplerian rotating disk is formed. This indicates that HCO+ traces the infalling-rotating envelope down to the CB and COMs trace the atmosphere of a Keplerian rotating disk within the CB. The COMs are spatially resolved for the first time, both radially and vertically, in the atmosphere of a disk in the earliest, Class 0 phase of star formation. Our spatially resolved observations of COMs favor their formation in the disk rather than a rapidly infalling (warm) inner envelope. The abundances and spatial distributions of the COMs provide strong constraints on models of their formation and transport in low-mass star formation.

Key words: accretion, accretion disks – ISM: individual objects (HH 212) – ISM: jets and outflows – stars: formation

1. Introduction

In theory of star formation, rotationally supported disks are expected to form inside collapsing cores, feeding the protostars at the center. They will have a Keplerian rotation if the mass of the protostars dominates that of the disks. In models of nonmagnetized core collapse, a Keplerian disk can indeed form as early as in the Class 0 phase (Terebey et al. 1984). However, a realistic model should include magnetic field, because a recent survey toward a few Class 0 sources shows 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 an efficient magnetic braking that removes the angular momentum and thus prevents a Keplerian disk from forming at the center (Allen et al. 2003; Mellon & Li 2008). In those cases, only a flattened envelope called the pseudodisk can be formed 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).

Before the advent of the Atacama Large Millimeter/submillimeter Array (ALMA), a few Class 0 disk candidates in, e.g., HH 212 (Codella et al. 2007; Lee et al. 2008), HH 211 (Lee et al. 2009), L1527 (Tobin et al. 2012), and VLA 1623 (Murillo & Lai 2013) have been identified. With ALMA, we have started to resolve their kinematics, which are found to be roughly Keplerian (Murillo et al. 2013; Sakai et al. 2014). In addition, we can also map the surrounding envelopes and study the transition from the envelopes to the disks (Lee et al. 2014; Sakai et al. 2014). Recent study at high resolution has even started to resolve the transition region between the envelope and disk in L1527 (Sakai et al. 2017).

HH 212 is a well-studied Class 0 protostellar system with evidence for a Keplerian disk resolvable with ALMA and thus a good target to study the disk formation and the transition from the envelope to the disk. It is deeply embedded in a compact molecular cloud core in the L1630 cloud of Orion, which is at a distance of about 400 pc (Kounkel et al. 2017). The central source is the Class 0 protostar IRAS 05413–0104, with a bolometric luminosity $L_{bol} \sim 9 L_{\odot}$ (updated for the distance of 400 pc; Zinnecker et al. 1992). It drives a powerful bipolar jet (Zinnecker et al. 1998; Lee et al. 2007). A Keplerian disk must have formed in order to launch the jet, according to current models of jet launching.

In previous ALMA Cycle 0 observations at ∼200 au (0″5) resolution, we have detected a flattened envelope in HCO+ with an outer radius of ∼1000 au around the central protostar (Lee et al. 2014). The envelope is infalling toward the center, spinning up at smaller radii in a manner that is consistent with angular momentum conservation. It can thus be identified as a pseudodisk in current models of the magnetized core collapse (Allen et al. 2003; Mellon & Li 2008). Based on the infall and rotation velocity profiles, we estimated a centrifugal radius (CR) of ∼120 au (0″3); thus, a Keplerian disk is expected to have formed closer in, with a radius <120 au. A similar disk radius was estimated based on the gas kinematics in C17O toward the center (Codella et al. 2014). Recently with ALMA observations at a resolution of ∼8 au (0″02), we have not only detected the disk but also spatially resolved the disk structure in dust continuum (Lee et al. 2017). The dusty disk has a radius of ∼60 au, which is half of the CR estimated before at low resolution.
resolution. A natural question is, is this the radius of the centrifugal barrier (CB) as found in L1527 (Sakai et al. 2014)? In addition, the disk structure is resolved in the vertical direction, showing a flared structure within ~40 au of the central protostar. Could this radius be the radius of the Keplerian disk? Without detailed kinematic study of the envelope and disk, we cannot determine the radius at which the Keplerian disk has formed.

In this paper, we will present our ALMA observations in HCO\(^+\) \(J = 4\rightarrow 3\) at \(\sim 24\rightarrow 40\) au resolutions, which is \(\sim 5\rightarrow 8\) times higher than the previous observations, in order to resolve the envelope structure and kinematics. At these high resolutions, we can resolve and model the infall velocity profile directly. Moreover, we also detect several complex organic molecules (COMs) in the disk atmosphere at \(\sim 16\) au resolutions, including methanol (CH\(_3\)OH), deuterated methanol (CH\(_3\)DOH), methyl mercaptan (CH\(_3\)SH), and formamide (NH\(_2\)CHO). COMs have been detected before around the CB or disks/envelopes in other protostellar systems (Sakai et al. 2014; Jørgensen et al. 2016; Oya et al. 2016). Here, we not only detect them but also spatially resolve their structure. Our observations not only provide conclusive evidence that our detected COMs are associated with the disk (as opposed to the rapidly infalling envelope or large-scale outflow), at least for this particular Class 0 source, but also enable us to show that the disk is rotating, with a profile consistent with Keplerian. The disk rotation would be difficult to determine without the COMs in the disk atmosphere above and below the optically thick dusty disk. Together, the new observations enable us to better discuss the transition of the envelope to the disk and the formation and kinematics of the disk.

### 2. Observations

Observations of the HH 212 protostellar system were carried out with ALMA in Band 7 at \(\sim 350\) GHz in Cycles 1 and 3, with 32–45 antennas (see Table 1). The Cycle 1 project was carried out with two executions, both on 2015 August 29 during the Early Science Cycle 1 phase. The projected baselines are 15–1466 m. The maximum recoverable size scale is \(\sim 2^\prime.5\). A five-pointing mosaic was used to map the system within \(\sim 15^\prime\) of the central source at an angular resolution of \(\sim 0.16\) (64 au). The Cycle 3 project was carried out with two executions in 2015, one on November 5 and the other on December 3, during the Early Science Cycle 3 phase. The projected baselines are 17–16,196 m. The maximum recoverable size scale is \(\sim 0.04\). One pointing was used to map the center of the system at an angular resolution of \(\sim 0.02\) (8 au). For the Cycle 1 project, the correlator was set up to have four spectral windows, with one for CO \(J = 3\rightarrow 2\) at 345.795991 GHz, one for SIO \(J = 8\rightarrow 7\) at 347.330631 GHz, one for HCO\(^+\) \(J = 4\rightarrow 3\) at 356.734288 GHz, and one for the continuum at 358 GHz, with possible other weak lines (see Table 2). For the Cycle 3 project, the correlator was more flexible and thus was set up to include two more spectral windows, with one for SO \(J = 8\rightarrow 7\) at 346.528481 GHz and one for H\(^13\)CO\(^+\) \(J = 4\rightarrow 3\) at 346.998338 GHz (see Table 3). The total time on the HH 212 system is \(\sim 148\) minutes.

The data were calibrated with the CASA package for the passband, flux, and gain (see Table 4). In this paper, we only present the observational results in HCO\(^+\), D\(_2\)CO, and four COMs (see Table 5), with HCO\(^+\) tracing the envelope and D\(_2\)CO and the COMs tracing the disk around the central source. The velocity resolution is \(\sim 0.212\) km s\(^{-1}\) per channel for the lines in the spectral line windows and \(\sim 0.848\) km s\(^{-1}\) per channel for the lines in the continuum window. Cycle 1 data and Cycle 3 data are combined to make the maps. For HCO\(^+\) maps, the data with the \(uv\)-distance greater than 3000 m (with a corresponding angular scale of \(\sim 0.06\)) are excluded because no HCO\(^+\) emission is detected there. We used a robust factor of 0.5 for the visibility weighting to generate the HCO\(^+\) maps at \(\sim 0.06\) resolution. In addition, we convolved the maps to 0.1 resolution to map the emission at low velocity, which is more extended. The noise levels can be measured from line-free channels and are found to be \(\sim 3.1\) mJy beam\(^{-1}\) (or \(\sim 10\) K) for \(\sim 0.06\) resolution and 3.9 mJy beam\(^{-1}\) (or \(\sim 3.75\) K) for \(\sim 0.1\) resolution. For the maps of the COMs, we used a robust factor of 0.5 and the data with the \(uv\)-distance shorter than 8000 m (with a corresponding angular scale of \(\sim 0.02\)) because of no detection at longer \(uv\)-distance. The resulting resolutions are \(\sim 0.04\). The noise levels are found to be \(\sim 1.7\) mJy beam\(^{-1}\) (or \(\sim 11\) K) for 0.848 km s\(^{-1}\) and 3.0 mJy beam\(^{-1}\) (or \(\sim 20\) K) for 0.212 km s\(^{-1}\). The velocities in the channel maps are LSR velocities.

### 3. Results

The systemic velocity in HH 212 is assumed to be \(V\_\text{sys} = 1.7 \pm 0.1\) km s\(^{-1}\) LSR, as in Lee et al. (2007). Throughout this paper, in order to facilitate our presentations, we define an offset velocity \(V\_\text{off} = V\_\text{LSR} − V\_\text{sys}\) and rotate our maps by 23° clockwise to align the jet axis in the north–south direction. The jet has an inclination of \(\sim 4^\circ\) to the plane of the sky, with the northern component tilted toward us (Claussen et al. 1998). A dusty disk has been detected perpendicular to the jet axis and found to be nearly edge-on with the near side tilted slightly by \(\sim 4^\circ\) to the south (Lee et al. 2017).

#### 3.1. Flattened Envelope in HCO\(^+\)

The envelope can now be better studied at higher angular resolutions. As before, HCO\(^+\) emission is detected near the equatorial plane within \(\sim 3\) km s\(^{-1}\) of the systemic velocity. Based on our analysis of the gas kinematics below and later in Section 3.3, the emission there shows an infall motion with some rotation and thus traces a flattened infalling-rotating envelope. In order to see the velocity distribution pictorially,
**Table 2**  
Correlator Setup for Cycle 1 Project

| Spectral Window | Line or Continuum | Number of Channels | Central Frequency (GHz) | Bandwidth (MHz) | Channel Width* (kHz) |
|-----------------|-------------------|--------------------|------------------------|----------------|---------------------|
| 0               | CO $J = 3\rightarrow 2$ | 3840 | 345.803 | 468.750 | 122.070 |
| 1               | SiO $J = 8\rightarrow 7$ | 3840 | 347.338 | 468.750 | 122.070 |
| 2               | HCO$^+$ $J = 4\rightarrow 3$ | 3840 | 356.742 | 468.750 | 122.070 |
| 3               | Continuum          | 3840 | 358.008 | 1875.000 | 488.281 |

Note.  
* Effective velocity resolution is about two channels in this cycle.

**Table 3**  
Correlator Setup for Cycle 3 Project

| Spectral Window | Line or Continuum | Number of Channels | Central Frequency (GHz) | Bandwidth (MHz) | Channel Width (kHz) |
|-----------------|-------------------|--------------------|------------------------|----------------|---------------------|
| 0               | SO $N_2 \rightarrow 8_8 - 7_8$ | 960 | 346.528 | 234.375 | 244.140 |
| 1               | CO $J = 3\rightarrow 2$ | 960 | 345.796 | 234.375 | 244.140 |
| 2               | H$^1$CO$^+$ $J = 4\rightarrow 3$ | 960 | 346.998 | 234.375 | 244.140 |
| 3               | SiO $J = 8\rightarrow 7$ | 960 | 347.330 | 234.375 | 244.140 |
| 4               | HCO$^+$ $J = 4\rightarrow 3$ | 1920 | 356.735 | 468.750 | 244.140 |
| 5               | Continuum          | 1920 | 357.994 | 1875.000 | 976.562 |

**Table 4**  
Calibrators and Their Flux Densities

| Date (YYYY MM DD) | Bandpass Calibrator | Flux Calibrator | Phase Calibrator |
|-------------------|---------------------|----------------|-----------------|
| 2015 Aug 29       | J0607+0834, 1.20 Jy | J0423–013, 1.03 Jy | J0552+0313, 0.25 Jy |
| 2015 Aug 29       | J0607+0834, 1.20 Jy | J0423–013, 1.03 Jy | J0552+0313, 0.25 Jy |
| 2015 Nov 05       | J0423–0120, 0.55 Jy | J0423–0120, 0.55 Jy | J0541–0211, 0.22 Jy |
| 2015 Dec 03       | J0510+1800, 4.07 Jy | J0423–0120, 0.67 Jy | J0541–0211, 0.23 Jy |

**Table 5**  
Line Properties from Splatalogue

| Molecule | Frequency (GHz) | Transition QNs | $S_{\mu,e}^2$ (D$^2$) | $\log_{10}(A_{\nu})$ (s$^{-1}$) | $E_{\nu}$ (K) | Line List |
|----------|----------------|----------------|------------------------|-------------------------------|--------------|-----------|
| CH$_2$DOH | 345.71872 | 3(2, 1)–3(1, 2), e1 | 0.61635 | $-4.37316$ | 39.43488 | JPL |
| CH$_3$DOH | 356.89967 | 8(2, 7)–7(2, 6), e1 | 5.77871 | $-3.74509$ | 103.67562 | JPL |
| CH$_3$DOH | 356.90507 | 8(5, 3)–7(5, 2), o1 | 3.71100 | $-3.93737$ | 192.93386 | JPL |
| CH$_3$DOH | 356.90507 | 8(5, 4)–7(5, 3), o1 | 3.71100 | $-3.93737$ | 192.93386 | JPL |
| CH$_3$DOH | 356.91471 | 8(2, 7)–7(2, 6), o1 | 5.99850 | $-3.72878$ | 112.57969 | JPL |
| CH$_3$DOH | 356.93242 | 8(4, 4)–7(4, 3), e1 | 4.51361 | $-3.85223$ | 149.20816 | JPL |
| CH$_3$DOH | 356.93244 | 8(4, 5)–7(4, 4), e1 | 4.51361 | $-3.85223$ | 149.20816 | JPL |
| CH$_3$DOH | 357.23327 | 8(2, 6)–7(2, 5), o1 | 6.01053 | $-3.72675$ | 112.61829 | JPL |
| CH$_3$DOH | 357.52856 | 7(1, 6)–7(0, 7), e1 | 6.14490 | $-3.66171$ | 77.13300 | JPL |
| CH$_3$DOH | 357.53536 | 8(6, 2)–7(6, 1), e0 | 2.19664 | $-4.16284$ | 216.82322 | JPL |
| CH$_3$DOH | 357.53536 | 8(6, 3)–7(6, 2), e0 | 2.19664 | $-4.16284$ | 216.82322 | JPL |
| CH$_3$DOH | 357.65950 | 8(5, 4)–7(5, 3), e0 | 2.96147 | $-4.03260$ | 174.61159 | JPL |
| CH$_3$DOH | 357.65950 | 8(5, 5)–7(5, 2), e0 | 2.96147 | $-4.03260$ | 174.61159 | JPL |
| CH$_3$DOH | 357.68738 | 8(2, 6)–7(2, 5), e1 | 5.77277 | $-3.74262$ | 103.77011 | JPL |
| CH$_3$DOH | 357.81966 | 8(4, 5)–7(4, 4), o1 | 3.57036 | $-3.95081$ | 140.21085 | JPL |
| CH$_3$DOH | 357.82025 | 8(4, 4)–7(4, 3), e1 | 3.57035 | $-3.95081$ | 140.21087 | JPL |
| CH$_3$DOH | 357.98957 | 8(6, 3)–7(6, 5), e0 | 3.94436 | $-3.90693$ | 113.18953 | JPL |
| CH$_3$DOH | 358.05489 | 8(3, 5)–7(3, 4), e0 | 3.94297 | $-3.90684$ | 113.19525 | JPL |
| CH$_3$OH | 345.90392 | 7(1, 15)–7(1, 14) | 6.18282 | $-4.04453$ | 332.65331 | JPL |
| CH$_3$OH | 358.41465 | 10(6, 5)–11(5, 7) | 1.34748 | $-4.46361$ | 306.42756 | JPL |
| CH$_3$OH | 358.60582 | 4(1, 3)–3(0, 3) | 2.21223 | $-3.87963$ | 44.26398 | JPL |
| CH$_3$SH | 356.62709 | 14(1)–13(1) E | 0.24000 | $-4.00147$ | 135.98637 | SLAIM |
| NH$_2$CHO | 356.71376 | 17(2, 16)–16(2, 15) | 218.95428 | $-2.48082$ | 166.78985 | CDMS |
| HCO$^+$ | 356.73422 | 4–3 | 60.83879 | $-2.44709$ | 42.80203 | CDMS |
| D$_2$CO | 357.87145 | 6(2, 4)–5(2, 3) | 57.94797 | $-2.92482$ | 81.21173 | CDMS |
Figure 1. ALMA HCO$^+$ maps toward the center of the HH 212 system, rotated by 22.5° clockwise to align the jet axis in the north–south direction. The star marks the position of the central protostar. The red and blue arrows indicate the axes of the redshifted component and blueshifted component of the jet, respectively. The jet has an inclination angle of ∼4° to the plane of the sky. The dotted parabolic curves delineate roughly the upper and lower boundaries of the HCO$^+$ envelope, as defined in Section 3.1. (a) Maps at low redshifted velocity ($V_{\text{off}} \sim 0$–1.5 km s$^{-1}$) and low blueshifted velocity ($V_{\text{off}} \sim -1.5$ to 0 km s$^{-1}$) at 0\farcs1 resolution. The contour levels start at 3 km s$^{-1}$ and high blueshifted velocity ($V_{\text{off}} \sim -3.0$ to $-1.5$ km s$^{-1}$) at 0\farcs06 × 0\farcs08 resolution, on top of the 351 GHz continuum map of the dusty disk adopted from Lee et al. (2017). The contour levels start at 3σ with a step of 2σ, where σ = 5 mJy beam$^{-1}$ km s$^{-1}$. We divide the velocity range into a low velocity range with $|V_{\text{off}}| \leq 1.5$ km s$^{-1}$ and a high velocity range with $1.5 \leq |V_{\text{off}}| \leq 3$ km s$^{-1}$.

Figure 1(a) shows the HCO$^+$ maps at low velocity at 0\farcs1 resolution. The redshifted and blueshifted emissions near the equatorial plane (indicated by the orange lines) within a radius of ∼2\arcmin of the central source trace the flattened envelope. Figure 1(b) shows the HCO$^+$ maps at high velocity at 0\farcs06 resolution. At high velocity, since the emission structure is more compact, a higher resolution is used. The innermost part of the envelope can be seen at high velocity down to ∼0\farcs1 of the central source. As can be seen from these two figures, the envelope is flared, with a thickness increasing with increasing distance from the central source. For simplicity, the boundaries of the envelope are assumed to have a parabolic structure, with $z = a + bR^2$ in the cylindrical coordinate system. Here $a$ is the position offset from the central source and $b$ is a constant describing the curvature. Using a rough eye fitting to the redshifted and blueshifted HCO$^+$ emission of the envelope at both low velocity (Figures 1(a)) and high velocity (Figure 1(b)), we obtained $a = 0.05$ and $b = 0.45$ for the upper boundary and $a = -0.05$ and $b = -0.6$ for the lower boundary, as delineated by the dotted parabolic curves. Note that since the boundaries are neither symmetric nor sharply defined, the parabolic curves are mainly used to guide the readers.

At low velocity as shown in Figure 1(a), the blueshifted emission of the envelope is seen across the central source, with the west side brighter than the east side. The redshifted emission is weaker and is seen mainly in the east. As discussed in Lee et al. (2014), this spatial distribution indicates that the envelope has mainly infall motion but some small rotation with the redshifted side in the east and the blueshifted side in the west. The redshifted emission is fainter and even absent in the west, due to a self-absorption in the near side of the infalling envelope (Evans 1999). An emission hole is seen at the center toward the dusty disk in both blueshifted and redshifted maps. This is because the dusty disk is bright and optically thick (Lee et al. 2017); thus, the emission behind it is blocked and the emission in front of it appears absorbed against the bright background. The emission above the upper envelope boundary and below the
lower envelope boundary traces the outflow and jetlike emission and will be discussed in a future publication.

At high velocity as shown in Figure 1(b), the redshifted and blueshifted emissions are now seen on the opposite sides within ∼0″3 of the central source surrounding the dusty disk, indicating that the motion there becomes dominated by the rotation. No emission is detected toward the dusty disk within ∼0″1 of the center, because the disk continuum emission becomes optically thick there (Lee et al. 2017). The redshifted emission extending slightly to the south from the lower boundary could trace a low-velocity outflow coming out of the envelope. The blueshifted emission above the upper disk surface and below the lower disk surface is from the infalling envelope in the far side that is not blocked by the disk.

Figure 2(a) shows the position–velocity (PV) diagram of the envelope cut along the major axis (equator). It shows a blueshifted triangular structure pointing toward the high blueshifted velocity and a redshifted triangular structure pointing toward the high redshifted velocity, similar to those seen before at a lower resolution of ∼0″45 (Lee et al. 2014). As discussed by the authors, these features are signatures of infall motion in the envelope, with the blueshifted triangular structure coming from the far side of the envelope and the redshifted structure from the near side. The blueshifted triangular structure shifts slightly to the west because of a small rotation (going from the east to the west in the far side) in the infalling envelope. The base of the redshifted triangular structure near the systemic velocity is absent, due to the self-absorption in the near side, which is infalling toward the central source and thus preferentially absorbs the redshifted part of the emission (Evans 1999). This absorption by the infalling envelope on the near side is the reason why there is little redshifted HCO+ emission on the west side of the central source. At higher angular resolution of ∼0″1, the high redshifted (≥1.5 km s−1) and high blueshifted (≤−2 km s−1) emissions near the central source are now seen on the opposite sides of the source, confirming that the motion there becomes dominated by the rotation.

At high resolution of ∼0″1, we can study the infall motion directly using the PV diagram of the envelope cut along the minor axis, as shown in Figure 2(b). The PV structure for the faint emission at high velocity with |V_{\text{eff}}| > 2 km s−1 should be mainly from the outflow and jetlike emission along the jet axis, as seen in Figure 7(b) in Lee et al. (2014). In addition, the emission on the redshifted side suffers significantly from the self-absorption. Therefore, we only focus on the low-velocity part (|V_{\text{eff}}| < 2 km s−1) on the blueshifted side as pointed by the arrows, and we model it in Section 3.3 below to see whether the infall velocity increases toward the center.

### 3.2. Tracing Disk Atmosphere with COMs

Line emissions from four COMs and D₂CO are detected toward the center (see Table 5). Figure 3 shows the integrated intensity maps of CH₃OH (methanol, three lines) and CH₂DOH (deuterated methanol, 18 lines at 13 frequencies) lines in various transitions. Since the emission morphology is similar, the maps of the same molecule are stacked together to make a map with a higher signal-to-noise ratio (S/N). Figure 4 shows the stacked maps of CH₃OH and CH₂DOH, along with the
Unlike HCO$^+$, the molecules CH$_3$OH, CH$_2$DOH, and CH$_3$SH are only detected within $\sim$40 au ($\sim$1") of the central source, and the molecules NH$_2$CHO and D$_2$CO are only detected closer in (within $\sim$30 au). Notice that CH$_2$DOH is a D-substituted methanol and CH$_3$SH is a sulfur analogue of methanol, and they both have the same spatial distribution as the methanol. The emission structures are more extended for CH$_3$OH, CH$_2$DOH, and CH$_3$SH than for NH$_2$CHO and D$_2$CO. The A-coefficients of these five molecules can be roughly divided into two groups, one for CH$_3$OH, CH$_2$DOH, and CH$_3$SH having a value of $\sim$10$^{-4}$ s$^{-1}$, and the other for NH$_2$CHO and D$_2$CO having a value of (1−3) $\times$ 10$^{-3}$ s$^{-1}$, as seen in Table 5. Thus, the difference in the spatial distribution of these molecules might be partly due to the different values of their A-coefficients, which could reflect different critical densities. These complex molecules are detected at $\sim$0.05 (20 au) above and below the midplane, and thus above the upper dusty disk surface in the north and below the lower dusty disk surface in the south. The observed morphologies are suggestive of the COMs tracing the outer layers (i.e., atmosphere) of the disk, although it is also plausible that they trace the base of a disk wind. We favor the former interpretation over the latter because, as we will show below, the radial component of the velocity for these layers is much smaller than the rotational component. In addition, based on our analysis of the gas kinematics below and later in Section 3.3, the emission there shows a Keplerian rotation and thus indeed traces the atmosphere of a Keplerian rotating disk. Again, no molecular line emission is detected toward the opaque dusty disk. Since the dusty disk is optically thick, we cannot determine whether this is because of an absorption against the bright dust continuum or because of no emission of these molecules in the disk. Since the disk midplane has a
temperature of ∼70 K at ∼40 au (Lee et al. 2017), these molecules could also be depleted onto the dust grains near the midplane at the observed radius. The emission is brighter in the south than in the north. This is in opposition to the dust emission, which is brighter in the north. The redshifted emission and blueshifted emission are seen on the opposite sides of the jet axis, confirming that the disk atmosphere traced by the COMs is rotating. Notice that in the south in the methanol and deuterated methanol maps, the blue and red emissions have some overlap at small radii, due to the low velocity resolution and (thermal and possibly turbulent) line broadening, as discussed later. The emission maps show mainly a two-peak structure in the atmosphere, with one peak to the east and the other to the west of the rotational axis, tracing the two limb-brightened edges of a rotating ring there, as discussed later. NH$_2$CHO and probably D$_2$CO could trace a rotating ring closer to the rotational axis than CH$_3$OH, CH$_2$DOH, and CH$_3$SH, because their emission peaks are closer in.

The stacked CH$_3$OH and CH$_2$DOH maps have sufficient S/N for kinematic study. Figures 5(a) and (b) show the PV diagrams obtained by cutting their emission across the upper (blue) and lower (red) disk atmospheres parallel to the disk major axis. Here the upper disk atmosphere means the atmosphere in the north above the dusty disk surface, and the lower disk atmosphere means the atmosphere in the south below the dusty disk surface. The PV structure is similar in these two molecules, in agreement with them coming from the same region in the disk atmosphere. In addition, the PV structures in the upper and lower disk atmospheres are also similar, indicating that the atmospheres on both sides of the disk have a similar motion. At low velocity ($|V_{\text{rel}}| < 2$ km s$^{-1}$), linear PV structures are seen across the rotational (jet) axis, as indicated by the solid lines, which are obtained from a single linear fit to the linear PV structures seen in both methanol and deuterated methanol. At the two ends of the linear structures, the velocity becomes differential and increases toward the center. We can map these PV structures using the stacked deuterated methanol map, which has a higher S/N than the stacked methanol map.

Figure 6(a) shows the maps for both the linear part (green contours) and the differential part (red and blue contours for redshifted and blueshifted emission, respectively). For the linear part, the map shows a band of emission above the upper dusty disk surface and a band below the lower dusty disk surface. For the differential PV part, both the blueshifted and redshifted emissions are seen on the two edges of the disk atmosphere. In the south, the emissions also extend inward to the rotational axis. As shown by the magenta lines, their scale height decreases as they go closer to the rotational axis, indicating that the disk atmosphere traced by COMs is flared, as discussed below. In addition, their thickness (FWHM) also decreases toward the rotational axis.

Figure 6(b) shows a cartoon to explain the PV and the emission structures of the line emission, by adding a disk

Figure 4. Redshifted (red contours) and blueshifted (blue contours) emission in the stacked maps of methanol and deuterated methanol and in the maps of CH$_3$SH (methyl mercaptan), NH$_2$CHO (formamide), and D$_2$CO (deuterated formaldehyde), on top of the dusty disk continuum map. The maps all have an angular resolution of ∼0.′′04. The upper energy level for the line transition in each molecule is indicated in the upper right corner. The contour levels all start at 3σ, with a step of 2σ for methanol and deuterated methanol and a step of 1σ for the rest. The noise levels σ are ∼2.8 mJy beam$^{-1}$ km s$^{-1}$ for methanol, 1.0 mJy beam$^{-1}$ km s$^{-1}$ for deuterated methanol, 3.0 mJy beam$^{-1}$ km s$^{-1}$ for methyl mercaptan, 3.5 mJy beam$^{-1}$ km s$^{-1}$ for formamide, and 4.3 mJy beam$^{-1}$ km s$^{-1}$ for deuterated formaldehyde.
atmosphere (outlined by the curves and lines) on the dusty disk (color disk, with the color changing from blue to orange for the cold to hot disk surface). As mentioned earlier, the disk is almost edge-on, with its near side tilted slightly by 4° to the south. The disk atmosphere is assumed to be flared with the scale height (magenta lines) increasing with the radius, like the dusty disk. As can be seen from the cartoon, we can only detect the outermost ring of the disk atmosphere, which is not blocked by the dusty disk. For the upper disk atmosphere, the front part of the ring is projected onto the dusty disk, due to the tilt, and thus is absorbed against the bright disk continuum emission. Hence, the observed linear PV structure and its associated emission are from the back part of the ring. For the lower disk atmosphere, the back part of the ring is blocked by the disk, and thus the observed linear PV structure and its associated emission are from the front part of the ring. The radial (infall or expansion) motion of the ring can be studied with the PV diagrams of methanol and deuterated methanol along the minor axis, as shown in Figures 5(c) and (d). It it clear from the PV diagrams that the infall velocity there has dropped to zero. It has a small range of velocities, probably due to thermal and turbulent (due to, e.g., shock) broadening in the line emission and the low velocity resolution of \( \sim 0.85 \text{ km s}^{-1} \) in the stacked maps.

Besides the outermost ring, the part of the disk atmosphere along the major axis (magenta lines) can also be detected, as shown in Figure 6(b). This part produces the blue- and redshifted emission in the disk atmosphere extending inward to the rotational axis, with a scale height decreasing toward the center, associated with the differential PV structure. For the upper disk atmosphere, the inner part is not detected because of the absorption against the dusty disk. For the lower disk atmosphere, the inner part can be detected, because the dusty disk, with density decreasing with height (Lee et al. 2017), becomes optically thin at the highest rim. This allows us to see the atmosphere further in, as seen in the observations.

### 3.3. Modeling the Kinematics of the Envelope and Disk

In this section, we adopt the toy model developed by Sakai et al. (2014), which has been used to reproduce the similar PV structures of the envelope and disk in L1527. In this model, the gas motion in the envelope is approximated by the motion of a particle with conservation of both specific angular momentum and total energy. If the total energy is negligible at large distances and the specific angular momentum \( l \) is conserved in the infalling material, then the radial velocity \( v_r \) and the rotation velocity \( v_\phi \) (where \( \phi \) is the azimuthal angle) at radius \( r \) from the protostar are given by

\[
v_r = - \frac{2GM}{r} \left( 1 - \frac{l^2}{r^2} \right) \quad (1)
\]

and

\[
v_\phi = \frac{l}{r} \quad (2)
\]

where \( M \) is the mass of the central protostar plus disk. The radius at which the gravitational acceleration is balanced by the
centrifugal force is given by

$$r_c = \frac{l^2}{2GM}.$$  

This is the CR, where the radial velocity is equal to the rotation velocity, both with a magnitude of $GM/l$. The radius at which all the kinetic energy is converted to the rotational motion is given by

$$r_0 = \frac{l^2}{2GM}.$$  

This is the radius of the CB, where $v_0 = 2GM/l$. It is half of the CR. The infalling and rotating gas cannot move inward of the CB, unless it loses kinetic energy and angular momentum. If the gas does lose kinetic energy and angular momentum, then a disk is expected to form with a Keplerian rotation.

The envelope outside the disk is flared with the structure outlined by the dotted parabolic curves in Figure 1(a). For given $l$ and $M$, we can derive model PV structures for the envelope along the major and minor axis, by calculating the highest and lowest velocities at each position offset from the central source. These model PV structures can then be used to fit the outer boundaries of the observed PV structures. From $M$, we also can calculate the Keplerian rotation for the disk. Thus, the observed kinematics of the envelope and disk atmosphere can be fitted simultaneously with only two parameters, $l$ and $M$.

The best-fit parameters to both the envelope and disk kinematics simultaneously are found to be $l = 140 \pm 30 \text{ au km s}^{-1}$ and $M = 0.25 \pm 0.05 \text{ } M_{\odot}$, by matching (1) the outer boundaries of the PV structures of the envelope along the major and minor axis, (2) the maximum velocity in the PV diagram of the envelope along the major axis at the CB, (3) the maximum infall velocity of the envelope at the protostar position, and (4) the differential PV structure seen in the disk. For the envelope, the fit is based more on the blueshifted side, because the redshifted side suffers from self-absorption. As can be seen in Figures 7(a) and (b), the model PV structures delineate the outer boundaries of the observed PV structures reasonably well on the blueshifted side, and they also appear reasonable on the redshifted side. The best-fit parameters result in a CB at $\sim 0''11 \pm 0''02$ with a maximum velocity of $\sim 3.2 \text{ km s}^{-1}$, roughly matching that seen in the observed PV structure in Figure 7(a). The maximum infall velocity is $\sim 1.6 \text{ km s}^{-1}$, similar to that seen at the source position in Figure 7(a) and similar to the maximum velocity in Figure 7(b). For the disk, as marked in the figure, the CB roughly matches the two end positions of the linear PV structures seen in methanol and deuterated methanol, and the Keplerian rotation also roughly matches the differential PV structures on both the redshifted and blueshifted sides. In summary, this simple toy model can broadly reproduce all the important features in the PV diagrams of the envelope and disk. The observed infall velocity indeed increases toward the center, as expected for a gravitational collapse.

### 3.4. Physical Condition in the Disk Atmosphere

With 18 deuterated methanol lines (at 13 frequencies) detected, we can construct a population diagram to estimate the mean excitation temperature and the column density of the molecule in the region traced by the COMs. It is a diagram that plots the column density per statistical weight in the upper energy state in the optically thin limit, $N_{u} / g_{u}$, versus the upper energy level $E_{u}$ of the lines. Here $N_{u} \approx (8\pi k u / \epsilon c^2 A_{u}) W$, where the integrated line intensity $W = \int T_B d\nu$, with $T_B$ being the brightness temperature.

The integrated line intensity of each transition can be measured toward the lower disk atmosphere, where the emission is better detected, using the total intensity map (integrated over velocity, as shown in Figure 3) with a $2\sigma$ cutoff. The resulting population diagram is shown in Figure 8. Fitting the data points of deuterated methanol, we estimate a mean excitation temperature of $165 \pm 85 \text{ K}$ and a mean column density of $(9.2 \pm 2.0) \times 10^{16} \text{ cm}^{-2}$. Since the data points are scattered as a result of the low S/N, the fitting results have a big uncertainty in excitation temperature. Nevertheless, the inferred excitation temperature is consistent with the temperature at peak abundance for (deuterated) methanol in warm-up models of hot cores, which is estimated to be $\sim 120 \text{ K}$ (Garrod & Widicus Weaver 2013) or $\sim 130 \text{ K}$ (Müller et al. 2016). This broad consistency supports the notion that the observed (deuterated) methanol is produced by warming of icy grains in the disk atmosphere. If this is indeed the case, the COM-producing icy
grains should stay high up in the disk atmosphere, with interesting implications for grain growth and settling that should be explored with detailed modeling in future investigations.

We also measure the integrated line intensity of the methanol lines. Since only three lines are detected and the data points are scattered, we cannot estimate the temperature and column density reliably for methanol. Since the methanol has a similar spatial distribution to the deuterated methanol, we assume the same temperature for the methanol and then estimate the column density. Based on the two lines with an upper energy level $E_u > 300$ K, which are less optically thick (with a peak brightness temperature close to 80 K), we can scale down the data points of methanol by 7.4 to roughly match the best-fit solid line of the deuterated methanol. This implies a column density of $\gtrsim (3.4 \pm 1.0) \times 10^{17}$ cm$^{-2}$ for methanol and thus an abundance ratio of $[\text{CH}_2\text{DOH}]/[\text{CH}_3\text{OH}] \lesssim 0.27$.

**Figure 7.** Fitting (purple curves) to the PV diagrams of the HCO$^+$ envelope cut along the major and minor axis, and the PV diagrams of CH$_3$OH and CH$_2$DOH disk atmosphere along the major axis. The contour levels are the same as in Figures 2 and 5. CB = centrifugal barrier.
Methanol lines have been detected before at $\sim0^\circ55$ resolution toward the center in 19 transitions, including the one here at 345.9039 GHz, with the upper energy level reaching 750 K (Leurini et al. 2016). The excitation temperature of the methanol was estimated to be $\sim295$ K. Thus, the temperature estimated here could be underestimated by a factor of $\sim2$.

The integrated line intensity of CH$_3$SH is $\sim88$ K km s$^{-1}$ toward the disk atmosphere in the southern hemisphere. Assuming the same excitation temperature of 165 K for CH$_3$SH, the column density is found to be $\sim1.0 \times 10^{17}$ cm$^{-2}$, using the rotation partition function in Xu et al. (2012). Thus, [CH$_3$OH]/[CH$_3$SH] $\sim 3.4$. The integrated line intensity is $\sim70$ K km s$^{-1}$ for NH$_2$CHO and 77 K km s$^{-1}$ for D$_2$CO. The excitation temperature of NH$_2$CHO and D$_2$CO is unknown. If we assume the same excitation temperature, then the column density is $\sim1.6 \times 10^{13}$ cm$^{-2}$ for NH$_2$CHO and $\sim3.2 \times 10^{13}$ cm$^{-2}$ for D$_2$CO.

4. Discussion

4.1. Comparing to Our Previous Model

Our toy model here is adopted from Sakai et al. (2014), and it can be considered as a modified version of our previous model. In our previous model, the infalling envelope was assumed to have a freefall motion produced by the gravity of the central source (protostar plus disk) and a small rotation with conservation of specific angular momentum (Lee et al. 2014). Here the infall motion is no longer a pure freefall, but a freefall reduced by the rotational energy according to the conservation of total energy. In this case, both the infall and rotation motions produce constraints on the mass of the central source. In addition, the infall velocity reaches a maximum value at the CR and then decreases to zero at the CB, providing a transition region for a disk to form. As a result, the disk does not form immediately at the CR as we assumed before, but it can form interior to the CB. In our best-fit model, the specific angular momentum is $\sim140$ au km s$^{-1}$, the same as before. However, the mass of the central source is $\sim0.25 M_\odot$, higher than before, which was $\sim0.18 M_\odot$. As discussed earlier, this is because the mass here gives rise to both the rotation and infall motions, instead of only the infall motion as assumed in our previous model. Hence, the resulting CR is $\sim88$ au ($0^\circ22$), smaller than that estimated before, which was $\sim120$ au ($0^\circ3$).

4.2. Formation of a Keplerian Disk

From the model results, we can investigate in detail the forming process of a rotationally supported Keplerian disk in an infalling-rotating envelope in the star formation. Figure 9 shows a schematic diagram of the envelope and disk within $\sim500$ au of the central source in HH 212. In our best-fit model to the gas kinematics in HCO$^+$ and the COMs, the CR is $\sim88 \pm 18$ au and the CB is at $\sim44 \pm 9$ au. This indicates that HCO$^+$ traces the infalling-rotating envelope extending down to $\sim44$ au and the COMs trace the atmosphere of a Keplerian rotating disk with a radius of $\sim44$ au. In addition, the innermost envelope in between the CR and the CB can be considered as a transition region, where the infall velocity decreases rapidly to zero so that the envelope can transform into a Keplerian disk. In the schematic diagram, the envelope structure is derived from the HCO$^+$ envelope, as described in Section 3.1. The disk is composed of two components: one is the dusty disk seen in continuum in Lee et al. (2017), and the other is the disk atmosphere (surface) seen here in COMs. The dusty disk has an outer radius of $\sim68$ au ($0^\circ17$). However, based on our model...
result, only the inner part within \(~44\) au can be the Keplerian rotating disk, while the outer part of the dusty disk is in the transition region.

In the dusty disk, the continuum emission is found to become optically thick at \(r \sim 40\) au, due to a rapid increase in density (Lee et al. 2017). Interestingly, this radius is similar to the radius of the CB, suggesting that the increase in density is caused by the rapid decrease of the infall velocity in the transition region, which is expected in our model. Since the infall velocity decreases to zero at the CB, the material there should be almost stagnated, causing the material to accumulate locally and the disk to become optically thick. Also due to this rapid decrease in the infall velocity, the rotation becomes larger than the infall motion in the transition region, causing the blueshifted emission and redshifted emission there to be seen on the opposite sides of the central source, as shown in Figure 1(b). In the transition region, the dust continuum emission is only detected in the midplane, as shown in the schematic model in Figure 9(b), suggesting that the envelope is denser near the midplane. This could be due to a magnetic effect. If the infalling material is magnetized with an hourglass magnetic field morphology, the material would be falling toward the midplane, as expected for a pseudodisk (Allen et al. 2003).

The dusty disk is flared and in vertical hydrostatic equilibrium (Lee et al. 2017), as expected for an accretion disk. More importantly, its scale height reaches the maximum value of \(~12\) au at \(r \sim 36\) au near the CB, where the peaks of the methanol, deuterated methanol, and methyl mercaptan emissions are detected. As discussed earlier, these emission peaks trace a warm ring in the disk atmosphere with a temperature of 165–295 K. This ring of warm emission could trace a weak shock, e.g., an accretion shock, produced by the rapid decrease of the infall velocity near the CB. Similar weak shocks have been detected in SO in other protostellar systems L1527 (Sakai et al. 2017) and HH 111 (Lee et al. 2016), marking the transition from an infalling envelope to a Keplerian rotating disk. The infall velocity there is almost zero (see Figures 5(c) and (d)), and the rotation velocity interior to that radius can be roughly fitted with a Keplerian rotation (see Figures 7(c) and (d)), indeed supporting that a Keplerian disk has formed there.

The disk mass integrating from \(r \sim 36\) au toward the center is \(~0.03\) \(M_\odot\), using the disk density profile derived from modeling the disk continuum emission in Lee et al. (2017), assuming that the continuum emission is the dust thermal emission. As discussed by the authors, this mass is an upper limit because significant continuum emission could come from dust scattering of the disk thermal emission. Thus, the mass of the central protostar is \(>0.22\) \(M_\odot\). As a result, the disk mass within \(~36\) au of the central protostar is \(<13\)\% of the protostellar mass, further supporting that the Keplerian disk indeed can form with a radius of \(~36\) au.

As discussed earlier, the infalling material has to lose a fraction of the kinetic energy and angular momentum in order to form a Keplerian disk. In our observations, the ring of warm molecular gas detected near the CB supports that a fraction of the kinetic energy has indeed been converted to thermal energy through the shock, if the ring is heated by a shock. In the transition region, a low-velocity outflow or wind is seen in HCO\(^+\) extending out from the lower surface in the east (see Figure 1(b)), which may carry away a fraction of the angular momentum. This low-velocity outflow may in turn be due to the magnetic braking (Allen et al. 2003). Further observations are needed to check whether such an outflow is also seen from other surfaces in the transition region.

4.3. Comparing to Other Class 0 and I Disks

Similar envelope kinematics and disk formation have been suggested in another Class 0 system, L1527 (Sakai et al. 2014, 2017). In that system, a geometrically thin infalling envelope is seen in molecular gas traced by CCH. It broadens up in the transition region before joining the Keplerian rotating disk, probably because an accretion shock heats up the material there (Sakai et al. 2017). A similar broadening behavior is also seen here in the transition region in dust continuum, although not in molecular gas traced by HCO\(^+\) (see Figure 9(b)). In L1527, the central mass is \(~0.18\) \(M_\odot\), the specific angular momentum in the envelope is \(\sim180\) \(au\ km\ s^{-1}\), and thus the CB is at \(~100\) au, about twice as large as in HH 212. A likely Keplerian rotating disk is also detected interior to the CB, with a radius of \(\sim100\) au. Similar disk radius has also been claimed in other Class 0 systems (Lee et al. 2009; Murillo et al. 2013; Yen et al. 2017).

A few Class I Keplerian disks have been claimed in Taurus (Harsono et al. 2014), with a radius of \(\lesssim100\) au, similar to that found in the Class 0 disks. According to Equation (4) in our model, the CB and thus the disk radius are proportional to the square of the specific angular momentum in the infalling envelope. Therefore, the small radius of those disks could be due to the low specific angular momentum of \(\lesssim200\) \(au\ km\ s^{-1}\) in their infalling envelopes, as in the Class 0 sources. Recently, a small Class I Keplerian disk with a slightly larger radius of \(\sim100–200\) au has also been detected in HH 111 in Orion (Lee et al. 2016). However, unlike the Class I sources in Taurus, HH 111 has a much larger specific angular momentum of \(\sim1550\) \(au\ km\ s^{-1}\) in its envelope. Its Keplerian disk is not much bigger than those in the Class 0 sources because a large fraction of the specific angular momentum is lost, probably due to magnetic braking (Lee et al. 2016). Thus, the disk radius could be affected significantly by other effects and hence becomes much smaller than the CB.

4.4. Complex Organic Molecules

Unlike HCO\(^+\), the COMs are only detected interior to the CB within \(~40\) au of the central protostar in the atmosphere of the flared disk. Their emission can be detected down to \(~10\) au of the central protostar. No emission is detected further in because the disk is bright and optically thick in dust continuum, and thus the emission is either blocked or absorbed against it. The emission of the methanol, deuterated methanol, and methyl mercaptan peaks near the CB and thus could be caused by a shock interaction in that region, as discussed earlier. On the other hand, since the disk is flared and thus exposed to the radiation of the central protostar, stellar radiative heating and/or mechanical heating (by a stellar or inner-disk wind) could play a role in warming the region where these molecules are detected. This is especially true for the molecules detected at small radii inside the CB, which is less affected by the envelope–disk transition, if at all. Formamide and deuterated formaldehyde are detected closer in, and thus their emission is more likely caused by the radiation heating of the protostar as well. No emission of these COMs is detected beyond \(~40\) au,
where the dusty disk is thinning out and thus could be self-shielded from the radiation (or outflow) of the protostar.

Our observations show the first spatially resolved detection of these COMs in the gas phase in the disk atmosphere in the Class 0 phase of star formation, opening up a window to study their formation mechanism. Methanol is known to be formed efficiently in the ice mantle of dust grains (Herbst & van Dishoeck 2009). Here the abundance ratio of $[\text{CH}_3\text{DOH}]/[\text{CH}_3\text{OH}] \lesssim 0.27$ is about 4 orders of magnitude higher than the cosmic abundance of deuterium of $\text{D}/\text{H} \sim 10^{-5}$. This high degree of deuteration strongly supports the formation of methanol and deuterated methanol in the ice mantle on the dust grains (Ceccarelli et al. 2001; Parise et al. 2006). We detect these molecules in the gas phase because they are desorbed (evaporated) from the dust grains, due to the heating by a shock and/or the radiation/outflow of the protostar. This scenario is supported by the fact that the excitation temperature inferred from the energy diagram for deuterated methanol is consistent with the temperature at peak abundance in models for producing this gas-phase molecule from warming of icy grains (see Section 3.4). Methyl mercaptan has the same spatial distribution as the methanol and thus could be formed on the dust grains as well. Recently, methyl mercaptan has been detected toward another low-mass star-forming region, IRAS 16293–2422, and argued to be formed in the ice mantle on the dust grains and then desorbed (Majumdar et al. 2016). Detection of doubly deuterated formaldehyde ($\text{D}_2\text{CO}$) is also an indicator of active grain surface chemistry (Ceccarelli et al. 2001). Formamide has been detected in both high-mass star-forming regions (Adande et al. 2013) and low-mass star-forming regions (Kahane et al. 2013; López-Sepulcre et al. 2015). It could be formed through the interaction between $\text{H}_2\text{CO}$ and $\text{NH}_3$ or $\text{NH}_3^+$ in the gas phase (López-Sepulcre et al. 2015). The spatial distribution is similar to that of $\text{D}_2\text{CO}$ and thus the implied $\text{H}_2\text{CO}$, supporting this formation mechanism. However, this molecule could also be formed on icy grain mantles, e.g., via hydrogenation of $\text{HNCO}$ (Mendoza et al. 2014; López-Sepulcre et al. 2015). It is detected closer to the protostar than the methanol, which is somewhat surprising in this scenario because, in the standard warm-up models of hot cores, its temperature at peak abundance ($\sim 120$ K) is very similar to that for methanol (and deuterated methanol), which is estimated to be $\sim 120$ K (Garrod & Widicus Weaver 2013) or $\sim 130$ K (Müller et al. 2016). The temperature at peak abundance for $\text{CH}_3\text{SH}$ is similar to that of $\text{NH}_2\text{CHO}$ ($\sim 120$ K), which is much higher than that of $\text{D}_2\text{CO}$ ($\sim 40$ K; R. Garrod 2017, private communication).

As a result, all of our detected COMs could be formed in the ice mantle on the dust grains, either in the envelope or in the disk. Recently, methanol has been detected in the gas phase in a protoplanetary disk (TW Hya) in the T Tauri phase of star formation, with its formation in the disk (Walsh et al. 2016). Here, our detected COMs are also more likely to be formed in the disk, either on the surface or in the midplane, and then brought to the surface by turbulence (Furuya & Aikawa 2014). This is because the COMs detected here are associated with the warm atmosphere of the disk rather than a rapidly infalling inner envelope that is warmed up by stellar radiation or some other means. This is important because icy grains can in principle stay longer in the rotationally supported disk than in the free-falling envelope, which would allow more time for the COMs to form (e.g., Jørgensen et al. 2005). On the other hand, if there is rapid grain growth, large grains may settle quickly toward the midplane, where the temperature may be too low to efficiently produce COMs. Our vertically resolved observations provide strong constraints for models of COM formation and transport.

Methanol has been proposed as a building block for more complex species of fundamental prebiotic importance, like amino acid compounds (Walsh et al. 2016). Formamide has also been proposed as a prebiotic precursor because it could lead to the synthesis of biomolecules, e.g., amino acids and amino sugars, which are the main components for the onset of both (pre)genetic and (pre)metabolic processes, respectively (Saladino et al. 2012). Therefore, the COMs have started to form on disks in the earliest phase of star formation and may play a crucial role in producing the rich organic chemistry needed for life.

5. Conclusions

We have spatially resolved the envelope and disk atmosphere in the HH 212 protostellar system with ALMA. Our primary conclusions are the following:

1. The envelope is detected in $\text{HCO}^+$ down to the dusty disk to within $\sim 40$ au of the central protostar. It has an infall motion with the infall velocity increasing toward the center, as expected for a gravitational collapse. It also has a rotation motion, which is lower than the infall motion in large radii but becomes higher than the infall motion near the dusty disk.

2. A rotating disk atmosphere is detected above and below the dusty disk in the COMs, including methanol ($\text{CH}_3\text{OH}$), deuterated methanol ($\text{CH}_3\text{DOH}$), methyl mercaptan ($\text{CH}_3\text{SH}$), and formamide ($\text{NH}_2\text{CHO}$), and in doubly deuterated formaldehyde ($\text{D}_2\text{CO}$), within $\sim 40$ au of the central protostar. These COMs are all spatially resolved, both radially and vertically, for the first time in the atmosphere of a disk in the earliest, Class 0 phase of star formation. These detections are made possible by ALMA long-baseline observations, which resolve both the dust and molecule line emission in the vertical direction.

3. The kinematics of the envelope and disk atmosphere can be reproduced simultaneously with a simple toy model, in which the envelope is collapsing with conservation of both specific angular momentum and total energy and the disk has a Keplerian rotation interior to the CB. In the best-fit model, the envelope has a specific angular momentum of $\sim 140 \pm 30$ km s$^{-1}$ au and the central source (protostar+disk) has a mass of $\sim 0.25 \pm 0.5$ $M_\odot$. The resulting CR is $\sim 88 \pm 18$ au, and the CB is at a radius of $\sim 44 \pm 9$ au. The innermost envelope in between these two radii can be considered as a transition region between a collapsing envelope and a Keplerian rotating disk. A Keplerian disk can indeed be formed with a radius of $\sim 40$ au.

4. Methanol, deuterated methanol, and methyl mercaptan are detected mainly in the disk atmosphere at a radius near the CB, although some are present further in down to a radius of $\sim 10$ au. Formamide and deuterated formaldehyde are detected within $\sim 30$ au of the central protostar.

5. Our detection of COMs in the warm disk atmosphere favors their formation on the disk rather than in the rapidly infalling inner (warm) envelope. Whether such molecules exist closer to the disk midplane cannot be determined for the nearly edge-on disk of HH 212 that is optically thick in...
The observed abundances and spatial distributions of the COMs provide strong constraints on models of their formation and transport.

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