L483: Warm Carbon-chain Chemistry Source Harboring Hot Corino Activity

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Abstract

The Class 0 protostar, L483, has been observed in various molecular lines in the 1.2 mm band at a subarcsecond resolution with ALMA. An infalling–rotating envelope is traced by the CS line, while a very compact component with a broad velocity width is observed for the CS, SO, HNCO, NH2CHO, and HCOOCH3 lines. Although this source is regarded as the warm carbon-chain chemistry (WCCC) candidate source at a 1000 au scale, complex organic molecules characteristic of hot corinos such as NH2CHO and HCOOCH3 are detected in the vicinity of the protostar. Thus, both hot corino chemistry and WCCC are seen in L483. Although such a mixed chemical character source has been recognized as an intermediate source in previous single-dish observations, we here report the first spatially resolved detection. A kinematic structure of the infalling–rotating envelope is roughly explained by a simple ballistic model with a protostellar mass of 0.1–0.2 \( M_\odot \) and a radius of the centrifugal barrier (half of the centrifugal radius) of 30–200 au, assuming an inclination angle of 80° (0° for face-on). The broad-line emission observed in the above molecules most likely comes from the disk component inside the centrifugal barrier. Thus, a drastic chemical change is seen around the centrifugal barrier.

Key words: ISM: individual objects (L483) – ISM: molecules – stars: formation – stars: pre-main sequence

1. Introduction

It is now recognized that low-mass star-forming regions show a significant chemical diversity, even if their evolutionary stages are almost the same (Class 0/Class I). Two distinct families so far identified are hot corino chemistry characterized by saturated complex organic molecules (COMs; e.g., Cazaux et al. 2003; Jørgensen et al. 2005) and warm carbon-chain chemistry (WCCC) characterized by unsaturated species (carbon-chain molecules; e.g., Sakai et al. 2008a, 2009a). A prototypical source for hot corino chemistry is IRAS 16293–2422 in Ophiuchus, while that for WCCC is L1527 in Taurus. Exclusive chemical compositions can be seen in these prototypical sources: carbon-chain molecules are deficient in the hot corino IRAS 16293–2422, while COMs are not detected in the WCCC source L1527 (Sakai et al. 2008b; Sakai & Yamamoto 2013). In addition, the existence of intermediate sources is also suggested by single-dish observations (e.g., Sakai et al. 2009a). Both the origin and evolution of the chemical diversity are important targets for astrochemistry.

Such diversity seems to originate from different chemical composition of the ice mantle at the onset of star formation (Sakai & Yamamoto 2013): WCCC sources are rich in CH4, while hot corinos are rich in saturated organic molecules. It is proposed that a duration time of the starless core after shielding the interstellar UV radiation could cause such a difference of the ice composition (Sakai et al. 2009a; Sakai & Yamamoto 2013). This mechanism is supported by a low deuterium fractionation in the WCCC source L1527 (Sakai et al. 2009b). On the other hand, it is also suggested that the environmental effects such as local variation of the UV radiation field and the effects by nearby star formation activities could be responsible for the chemical diversity (Lindberg et al. 2015; Spezzano et al. 2016). In any case, sources whose chemical compositions are intermediate between those of hot corinos and WCCC sources (or a mixture of the two) are naturally expected. Recent infrared observations indeed indicate the coexistence of CH4 and CH3OH ices (Graninger et al. 2016). This result implies that the intermediate sources could be a common occurrence. It is thus important to characterize such intermediate sources for understanding the chemical diversity and its origin.

On the other hand, the evolution of the chemical diversity to the protostellar disk has recently been studied toward both hot corinos and WCCC sources at a high spatial resolution with ALMA (Oya et al. 2014, 2015, 2016; Sakai et al. 2014a, 2014b, 2016; Imai et al. 2016). The observations revealed that these protostellar cores have different chemical compositions even at a spatial scale of a few tens of au around a protostar, where a disk structure is being formed. More importantly, the chemical compositions drastically change near the protostar. In the WCCC sources L1527 (Sakai et al. 2014a, 2014b) and TMC–1A (Sakai et al. 2016), carbon-chain molecules and CS exist in an envelope rotating and infalling toward its centrifugal barrier at radii of 100 and 50 au, respectively, while SO is concentrated around the centrifugal barrier. On the other hand,
H₂CO is present ubiquitously in the envelope, the centrifugal barrier, and the disk inside the barrier. In the hot corino source IRAS 16293–2422 A, C¹⁴S and OCS exist in an infalling–rotating envelope, COMs mainly around its centrifugal barrier, and H₂CS in both the envelope and disk components (Oya et al. 2016).

Chemical composition in the vicinity of the protostar is of fundamental importance, because it will define interstellar chemical heritage to protoplanetary disks. However, a few sources, including two WCCC sources (L1527 and TMC–1A; Sakai et al. 2014a, 2014b, 2016; Oya et al. 2015) and three hot corinos (IRAS 2A, IRAS 16293–2422 A, and B335; Maury et al. 2014; Imai et al. 2016; Oya et al. 2016), have been studied so far for chemical characterization at a 100 au scale. Hence, observations of other protostellar sources, including the sources with intermediate chemical compositions, are still awaited. In this study, we focus on the well-studied Class 0 protostar in L483.

The L483 dark cloud is located in the Aquila Rift (d = 200 pc; Jørgensen et al. 2002; Rice et al. 2006), which harbors the Class 0 protostar IRAS 18148–0440 (Fuller et al. 1995; Chapman et al. 2013). Its bolometric luminosity is 13 L☉ (Shirley et al. 2000). We here adopt the systemic velocity of 5.5 km s⁻¹ for this source based on previous single-dish observations (Hirota et al. 2009). In this source, the C₃H abundance is relatively high, and it is regarded as a possible candidate for the WCCC source (Sakai et al. 2009a; Hirota et al. 2009, 2010; Sakai & Yamamoto 2013). Recent detection of the novel carbon-chain radical HCCO further supports the carbon-chain-molecule- rich nature of this source (Agúndez et al. 2015). The outflow of L483 has been extensively studied (Fuller et al. 1995; Hatchell et al. 1999; Park et al. 2000; Tafalla et al. 2000; Jørgensen 2004; Takakuwa et al. 2007; Chapman et al. 2013; Leung et al. 2016). It is extended along the east–west axis, where the eastern and western components are redshifted and blueshifted, respectively. The position angle (P.A.) of the outflow axis is reported to be 95° by Park et al. (2000) based on the HCO⁺ (J = 1–0) observation and 105° by Chapman et al. (2013) based on the shocked H₂ emission reported by Fuller et al. (1995). The inclination angle of the outflow axis is reported to be ~50° with respect to the plane of the sky (0° for a face-on configuration; Fuller et al. 1995). Along the line perpendicular to the outflow, the northern part is blueshifted, while the southern part is redshifted, according to the CS (J = 2–1, 7–6) and HCN (J = 4–3) observations (Jørgensen 2004; Takakuwa et al. 2007). This suggests a rotating motion of the envelope. Chapman et al. (2013) reported the P.A. of a pseudo-disk to be 36° based on their Spitzer 4.5 μm observation.

In these previous studies, the disk/envelope system is not well resolved, and little is known about the chemical composition in the closest vicinity of the protostar. In the present study, we investigate the physical and chemical structures around the protostar at a 100 au scale with ALMA.

### 2. Observation

The ALMA observation of L483 was carried out in the Cycle 2 operation on 2014 June 12. Spectral lines of CCH, CS, SO, HNCO, t-HCOOH, CH₃CHO, NH₂CHO, HCOOCH₃, (CH₃)₂O, 

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Table 1 Parameters of the Observed Lines

| Molecule           | Transition | Frequency (GHz) | Eₚ (K) | S₀² (D¹⁰) | A₀ (s⁻¹) | Synthesized Beam |
|--------------------|------------|----------------|--------|-----------|---------|-----------------|
| CS                 | J = 5–4   | 244.935565     | 35.3   | 19        | 2.98 × 10⁻⁴ | 0.51 × 0.46 (P.A. = 177°24) |
| NH₄CHO             | 120,12–110,11 | 247.390719     | 78.1   | 157       | 1.10 × 10⁻³ | 0.56 × 0.49 (P.A. = 164°44) |
| HCOOCH₃            | 290–16–190,15; A | 249.0474280     | 141.6  | 50        | 1.46 × 10⁻³ | 0.52 × 0.45 (P.A. = 177°18) |
| SiO²               | J = 6–5   | 260.518000     | 43.8   | 58        | 9.12 × 10⁻⁴ | 0.46 × 0.42 (P.A. = 177°78) |
| CH₃CHO             | 141,14–131,15; A | 260.5440195     | 96.3   | 82        | 6.25 × 10⁻⁴ | 0.46 × 0.42 (P.A. = 177°31) |
| SO                 | J₂ = 6r–5r | 261.8437210    | 47.6   | 16        | 2.28 × 10⁻⁴ | 0.46 × 0.42 (P.A. = 3°09)   |
| CCH¹               | N = 3–2, J = 7/2–5/2, F = 4–3 and F = 3–2 | 262.0042600     | 25.1   | 2.3       | 5.32 × 10⁻⁵ | 0.98 × 0.92 (P.A. = 78°06) |
| t-HCOOH            | 120,12–110,11 | 262.103481      | 1.7    | 1.7       | 5.12 × 10⁻⁵ | 0.98 × 0.92 (P.A. = 78°06) |
| (CH₃)₂O           | 133,3–133,3; EE | 262.393513      | 118.0  | 143       | 7.18 × 10⁻⁵ | 0.46 × 0.41 (P.A. = 1°69)   |
| HNCO              | 120,12–110,11 | 263.7486250     | 82.3   | 30        | 2.56 × 10⁻⁴ | 0.48 × 0.41 (P.A. = 3°87)   |

Notes.

¹ Taken from CDMS (Müller et al. 2005) and JPL (Pickett et al. 1998).
² Nuclear spin degeneracy is not included.
³ Four channels binned. The spectral profiles of the HCOOCH₃ and t-HCOOH line (Figure 10) is obtained with binding 16 channels.
⁴ An outer taper of 1" is applied.

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**Figure 1.** Map of the dust continuum at 1.2 mm. The contour levels are 3σ, 5σ, 10σ, 20σ, 40σ, 80σ, and 160σ, where the rms level is 0.13 mJy beam⁻¹. The synthesized beam size is 0.46 × 0.42 (P.A. = 11°79).
and SiO were observed with the B and 6 receiver in the frequency range from 245 to 264 GHz (Table 1). Thirty-four antennas were used in the observation, where the baseline length ranged from 18.5 to 644 m. The field center of the observation was \((\alpha_{2000}, \delta_{2000}) = (18^h17^m29^s9.10, -04^d39'39.60)\). The primary beam size (FWHM) is 23\(^\circ\)03. The total on-source time was 25.44 minutes, where a typical system temperature was 60–120 K. A backend correlator was tuned to a resolution of 61.030 kHz and a bandwidth of each chunk of 58.5892 MHz. The resolution corresponds to the velocity resolution of 0.073 km s\(^{-1}\) at 250 GHz. J1733-1304 was used for the bandpass calibration and for the phase calibration every 7 minutes. An absolute flux density scale was derived from Titan. The data calibration was performed in the antenna-based manner, and uncertainties are less than 9%.

Images were obtained by using the CLEAN algorithm, where the Briggs’s weighting with the robustness parameter of 0.5 was employed. We applied self-calibration for better imaging. A continuum image was prepared by averaging line-free channels, and the line maps were obtained after subtracting the continuum component directly from the visibilities. Synthesized beam sizes

![Figure 2](image1.png)

**Figure 2.** Integrated intensity maps of (a) CCH \((N = 3–2, J = 7/2–5/2, F = 4–3\) and \(3–2\)) and (b) CS \((J = 5–4\)). The black contours represent the 1.2 mm continuum map, where the contour levels are 10\(\sigma\), 20\(\sigma\), 40\(\sigma\), 80\(\sigma\), and 160\(\sigma\), where the rms level is 0.13 mJy beam\(^{-1}\). The outflow axis is along the red arrow with a P.A. of 105\(^\circ\) in panel (b). The PV diagram in Figure 8 is prepared along the red arrow with a P.A. of 15\(^\circ\) in panel (b), which is centered at the position with an offset of 4\(^\prime\) to the southeast from the continuum peak along a P.A. of 105\(^\circ\).

![Figure 3](image2.png)

**Figure 3.** Integrated intensity maps of (a) SO \((J = 6–5\)) and (b) HNO \((J=5–4\)) and (c) NH\(_2\)CHO \((J=5–4)\) and (d) HCOOCH\(_3\) \((20_{8,6}–19_{8,6};\ A)\). The contours represent the 1.2 mm continuum map, where the contour levels are the same as those in Figure 2.

![Figure 4](image3.png)

**Figure 4.** Integrated intensity map of SiO \((J = 6–5)\). The white contours represent the 1.2 mm continuum map, where the contour levels are the same as those in Figure 2.
The total flux of the continuum is 0.13 mJy beam$^{-1}$, while those for CCH, CS, SO, HNCO, NH$_2$CHO, HCOOCH$_3$, and SiO maps are derived from the nearby line-free channels to be 8.2, 7.6, 6.1, 6.5, 4.4, 5.8, and 3.5 mJy beam$^{-1}$, respectively, for the channel width of 61.030 kHz.

for the spectral lines are listed in Table 1. An rms noise level for the continuum is 0.13 mJy beam$^{-1}$, while those for CCH, CS, SO, HNCO, NH$_2$CHO, HCOOCH$_3$, and SiO maps are derived from the nearby line-free channels to be 8.2, 7.6, 6.1, 6.5, 4.4, 5.8, and 3.5 mJy beam$^{-1}$, respectively, for the channel width of 61.030 kHz.

3. Distribution

Figure 1 shows the map of the 1.2 mm dust continuum, where the synthesized beam size is 0.076$\times$ 0.072 (P.A. 15$^\circ$79). Its peak position is determined by the two-dimensional Gaussian fit to be $(\alpha_{2000}, \delta_{2000}) = (18^h17^m29^s947, -04^d39^m39^s55)$. The deconvolved size of the continuum emission is 0.076$\times$ 0.072 (P.A. 158$^\circ$), and hence the image is not resolved. The total flux of the continuum is 28 mJy.

In this observation, we detected the lines of CCH, CS, SO, HNCO, NH$_2$CHO, HCOOCH$_3$, and SiO. This observation toward L483 is part of a larger project to delineate physical and chemical structures of the disk-forming regions in several protostellar sources with ALMA (Oya et al. 2013.1.01102.S; P.I. N. Sakai), and the above lines are all detected in the other sources (B335 and NGC 1333 IRAS 4A) with the same frequency setup (Imai et al. 2016; López-Sepulcre et al. 2017). Hence, their detections are secure, although only one line was detected for each of these species except for CCH. As mentioned in Section 1, this source is regarded as a WCCC candidate source (Hirota et al. 2009, 2010; Sakai et al. 2009a). Hence, detections of COMs such as NH$_2$CHO and HCOOCH$_3$, which are characteristic of hot corinos, are notable (e.g., Sakai & Yamamoto 2013). The integrated intensity maps of CCH, CS, SO, HNCO, NH$_2$CHO, HCOOCH$_3$, and SiO are shown in Figures 2–4.

The CCH ($N = 3–2$, $J = 7/2–5/2$, $F = 4–3$ and 3–2) emission is extended over a 10$''$ scale, and hence the outer taper of 1$''$ is applied to improve the signal-to-noise ratio (S/N) of the image (Figure 2(a)). The existence of the carbon-chain molecule CCH around the protostar at a few hundreds of au scale confirms the WCCC nature of this source. The CCH distribution has a hole with a radius of $\sim$0$''$.5 around the continuum peak. This feature is similar to that found in the WCCC sources L1527 and IRAS 15398–3359 (Oya et al. 2014; Sakai et al. 2014a, 2014b), which would originate from the gas-phase destruction and/or depletion onto dust grains. The hole of the distribution seems to have a slight offset from the continuum peak to the western side, which implies an asymmetric distribution of the gas in the vicinity of the protostar. This asymmetry may be related to inhomogeneities of the initial gas distribution. In addition to the envelope component, a part of the CCH emission seems to trace an outflow cavity wall. The direction of the outflow axis looks consistent with the previous reports (P.A. = 95$^\circ$–105$^\circ$, e.g., Park et al. 2000; Tafalla et al. 2000; Chapman et al. 2013).

The CS ($J = 5–4$) emission also traces the component extended over 10$''$ (Figure 2(b)). In addition, it shows a compact component concentrated to the continuum peak. The deconvolved size of this compact component is 1$''$.26 $\times$ 0$''$.88

Figure 5. Moment 1 maps of (a) SO ($J_u = 6_7-5_6$) and (b) HNCO (12$_{0,12}$–11$_{0,11}$). The black contours represent the 1.2 mm continuum map, where the contour levels are the same as those in Figure 2. The PV diagrams in Figures 7, 9, 11, and 15 are prepared along the black arrow in panel (a) (P.A. = 15$^\circ$) and along the direction perpendicular to it centered at the continuum peak.

Figure 6. Schematic illustration of the disk/envelope system in L483. The midplane of the disk/envelope is extended along a P.A. of 15$^\circ$, and its western side faces the observer. The line emission on the western side of the protostar are the same as those in Figure 2. The PV diagrams in Figures 7, 9, 11, and 15 are prepared along the black arrow in panel (a) (P.A. = 15$^\circ$) and along the direction perpendicular to it centered at the continuum peak.
and is slightly more extended than the 1.2 mm dust continuum. This slightly extended component will be discussed in Section 4. On the other hand, the SO ($J = 6_{7} - 5_{6}$), HNCO (120,12−110,11), NH$_2$CHO (120,12−110,11), and HCOOCH$_3$ (205,16−19,15; A) distributions are highly concentrated to the continuum peak (Figure 3). The sizes of the distributions deconvolved by the synthesized beam are 0\'\'56 × 0\'\'39 (P.A. 92°) and 0\'\'26 × 0\'\'16 (P.A. 42°) for SO and HNCO, respectively. The HNCO distribution is almost point-like. Similarly, the distributions of NH$_2$CHO and HCOOCH$_3$ are also point-like at the resolution of the observations. In addition to NH$_2$CHO and HCOOCH$_3$, we tentatively detected the t-HCOOH emission concentrated near the protostar.

The distribution of SiO ($J = 6−5$) is different from those of the above molecular species. It has a slight extension toward the northeastern direction from the continuum peak, as shown in Figure 4. The extension is significant, considering the synthesized beam of this observation (∼0\'\'5). The size of the SiO distribution deconvolved by the synthesized beam is 0\'\'70 × 0\'\'43 (P.A. = 35°).
compact high-velocity-shift component concentrated toward the protostar, whose maximum velocity shift from the systemic velocity (5.5 km s\(^{-1}\)) is as high as about 6 km s\(^{-1}\).

Along the line perpendicular to the disk/envelope direction (P.A. = 105\(^\circ\)), a component extended over a 20\(^\prime\) scale is observed (Figure 7(b)). Although this component looks complicated in the velocity structure, it likely traces a part of the outflow cavity. Figure 8 shows the PV diagram along the line across the outflow lobe on the southeastern side of the protostar, which is indicated by an arrow in Figure 2(b). The elliptic feature of the PV diagram characteristic of the outflow cavity wall is clearly observed. Although both the redshifted and blueshifted components with respect to the systemic velocity (5.5 km s\(^{-1}\)) are seen, the center velocity of the elliptic feature is slightly redshifted. This elliptic feature is consistent with the configuration illustrated in Figure 6. It is quite similar to that observed in the nearly edge-on outflow system of IRAS 15398–3359 (Oya et al. 2014), where both the redshifted and blueshifted components can be seen in each outflow lobe. Hence, it is most likely that the outflow of L483 blows nearly on the plane of the sky at least in the vicinity of the protostar, in contrast to previous reports (e.g., Fuller et al. 1995). Hence, the disk/envelope system likely has a nearly edge-on geometry (i \sim 80\(^\circ\)). The detailed structure of the outflow will be reported in a separate publication (Y. Oya et al. 2017, in preparation).

Assuming that the outflow axis is perpendicular to the midplane of the disk/envelope system, the northwestern side of the disk/envelope system will face the observer. If there is an infall motion in the envelope component, the northwestern and southeastern sides of the protostar would be blueshifted and redshifted, respectively, in the PV diagram along a P.A. of 105\(^\circ\) (Figure 7(d)). However, this feature is not clearly recognized, because of overwhelming contributions from the outflow component and the missing of the blueshifted component. The velocity gradient due to the infalling motion will be verified with the aid of the kinematic model in Section 5. On the other hand, the high-velocity-shift component does not show any velocity gradient along the P.A. of 105\(^\circ\) around the protostar position.

### 4.3. SO and HNCO

The PV diagrams of SO \((J_N = 6_2−5_1)\) and HNCO (12\(_{0,12}−11_{0,11}\)) are shown in Figure 9. Along the disk/envelope direction, a slight velocity gradient is seen for SO (Figure 9(a)), while it is scarcely recognized for HNCO (Figure 9(c)). This velocity gradient in SO is consistent with that found in CS; hence, it seems to originate from the rotation motion in the inner part of the disk/envelope system. No definitive velocity gradient along the line perpendicular to the disk/envelope direction can be seen for SO and HNCO in Figures 9(b) and (d). Hence, the SO and HNCO emission reveals no significant infalling motion in the vicinity of the protostar.

The high-velocity-shift components of SO and HNCO near the protostar position correspond to that found in the CS emission (Figure 7). Figure 10 shows the line profiles of CS, SO, and HNCO in a circular region with a diameter of 0"5 centered at the continuum peak. The line profile of SO shows a profile similar to that of CS, except for the self-absorption in CS. Their broad-line widths reflect the high-velocity-shift component concentrated around the protostar shown in Figures 7, 9(a), and 9(b). HNCO also shows a component
whose velocity shift from the systemic velocity is larger than $5\,\text{km\,s}^{-1}$. However, the redshifted component is brighter than the blueshifted component. This feature is also seen in its PV diagrams (Figures 9(c) and (d)). This implies that the HNCO distribution is asymmetric in the vicinity of the protostar. This asymmetry implies less gas in the southwestern part of the disk/envelope system (Figure 6).

4.4. $\text{NH}_2\text{CHO}$ and $\text{HCOOCH}_3$

The most notable result in this study is detections of the COMs, $\text{NH}_2\text{CHO}$ and $\text{HCOOCH}_3$. These two species are concentrated around the protostar, as shown in the moment 0 maps (Figures 3(c), (d)). The spectral line profiles of $\text{NH}_2\text{CHO}$ and $\text{HCOOCH}_3$ toward the protostar position are dominated by a redshifted component (Figure 10), which is similar to the HNCO spectrum. Since the redshifted component is enhanced for all the HNCO, $\text{NH}_2\text{CHO}$, and $\text{HCOOCH}_3$ spectra consistently, their detections are secure, i.e., they do not correspond to other species/ transitions. The redshifted line profile implies an asymmetric distribution of those molecules in the vicinity of the protostar, as mentioned in Section 4.3. However, the origin of the asymmetry is puzzling and is left for future high spatial resolution observations.

5. Analysis with the Infalling–Rotating Envelope Model

In order to understand the chemical differentiation observed above in terms of the physical structure around the protostar, we analyze the kinematic structure of the disk/envelope system. In L1527, TMC–1A, and IRAS 16293–2422 A, the kinematic structures of the infalling–rotating envelopes are successfully explained by a simple ballistic model (Sakai et al. 2014b, 2016, Oya et al. 2015, 2016). Hence, we apply the same model to the CS data. However, we cannot reproduce the overall velocity structure with the infalling–rotating envelope model. As explained below, we need to consider the two physical components: the infalling–rotating envelope and the centrally concentrated component.

The infalling–rotating envelope model employed in this study is essentially the same as that reported by Oya et al. (2014). Since we are interested in the velocity structure of the
infalling–rotating envelope, the key model parameters are the protostellar mass \( M \), the radius of the centrifugal barrier \( r_{\text{CB}} \), and the inclination angle of the disk/envelope system \( i \). Here, we assume a flattened envelope with a constant thickness (30 au), which has a radial density distribution of \( r^{-1.5} \), for simplicity. Unfortunately, the key parameters can loosely be constrained from these observations because of the contamination of the overwhelming centrally concentrated component. Hence, we calculate the models with various parameters to find the reasonable set of the parameters by eye. Figures 11(a) and (b) show an example of the simulation of the infalling–rotating envelope that reproduces the observed PV diagrams as much as possible, except for the central high-velocity components. The model parameters are a protostellar mass \( M \) of 0.15 \( M_\odot \) and a radius of the centrifugal barrier \( r_{\text{CB}} \) of 100 au. Since a nearly edge-on geometry is suggested by the outflow structure (Section 4.2), we roughly assume an inclination angle with respect to the plane of the sky \( i \) of 80° (0° for a face-on configuration; Y. Oya et al. 2017, in preparation). The infalling motion along the direction perpendicular to the disk/envelope system can marginally be recognized in the PV diagram with the aid of the model (Figure 11(b)). Its blueshifted part is missing, probably due to the asymmetric gas distribution mentioned above (Section 4.3).

To see how the model PV diagram depends on the radius of the centrifugal barrier \( r_{\text{CB}} \) and the protostellar mass \( M \), we also conducted the simulations of the PV diagrams along the disk/envelope direction and along the direction perpendicular to it by using the infalling–rotating envelope model with various sets of these two parameters, as shown in Figures 12 and 13, respectively. For the case of no rotation \( r_{\text{CB}} = 0 \) au, the positions of the most blueshifted component and the most redshifted component coincide in the model, which apparently contradicts with the observation (Figure 12). On the other hand, the velocity of the counter velocity component, which represents the infalling motion of the infalling–rotating envelope, is underestimated for the \( r_{\text{CB}} = 300 \) au case. As for the mass of the protostar, 0.05 and 0.5 \( M_\odot \) do not reproduce the PV diagram. Above all, a reasonable agreement is obtained, except for the central high-velocity components, for the range of \( r_{\text{CB}} \) from 30 to 200 au and the range of the protostellar mass from 0.1 to 0.2 \( M_\odot \). Hence, the \( r_{\text{CB}} \) of 100 au and the protostellar mass of 0.15 \( M_\odot \) are chosen as the representative values, as mentioned above (Figure 11). For more stringent constraints, further detailed analysis with a high angular resolution observation is needed. The infalling motion has a higher velocity shift than the observation if the model parameters are set to explain the high-velocity-shift component centrally concentrated near the protostar. This justifies the two-component model consisting of the infalling–rotating envelope and the centrally concentrated component described above. Although we can see some excess redshifted emission in the southwestern part of the PV diagram (Figure 11(a)), the model can roughly reproduce the infalling–rotating envelope part of the PV diagrams. We analyze the high-velocity component in a separate way, as described below.

The most likely candidate for the centrally concentrated high-velocity component traced by CS, SO, HNCO, \( \text{H}_2\text{CHO} \), and HCOOCH\(_3\) is the Keplerian disk inside the centrifugal barrier, although the rotation curve is not resolved. Assuming \( M \) of 0.15 \( M_\odot \) and \( i \) of 80°, which are roughly estimated from the above analysis of the infalling–rotating envelope, we can

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**Figure 10.** Spectral line profiles of CS \((J = 5–4)\), SO \((J_N = 6–5)\), HNCO \((12_{0,12}–11_{0,11})\), \( \text{NH}_2\text{CHO} \) \((12_{0,12}–11_{0,11})\), HCOOCH\(_3\) \((20_{16}–19_{15})\) A), and t-HCOOH \((12_{0,12}–11_{0,11})\) toward the protostar position. The line intensities are averaged in a circular region with a diameter of 0.5" centered at the continuum peak. The original spectra are smoothed to improve the S/N, so that the velocity resolution is 0.5 km s\(^{-1}\) for CS, SO, HNCO, and \( \text{NH}_2\text{CHO} \) and 1 km s\(^{-1}\) for HCOOCH\(_3\) and t-HCOOH.
reproduce the high-velocity-shift part of the PV diagrams of CS and SO by the Keplerian disk model (Figures 11 and 14). A radius of the emitting region of the maximum velocity-shift component (~6 km s^{-1}) in the disk is estimated to be as small as 4 au. We also show the results of the Keplerian disk model combined with the infalling–rotating envelope model in Figure 15. In addition, the results of the Keplerian disk model are overlaid on those of the infalling–rotating envelope model in Figures 12 and 13 for reference.

In L483, the kinematic structure of the gas traced by CS around the protostar is similar to those of H_{2}CO in L1527 and H_{2}CS in IRAS 16293–2422 A, which are explained by a combination of the infalling–rotating envelope component and the (possible) Keplerian disk component inside the centrifugal barrier (Sakai et al. 2014b; Oya et al. 2016). Hence, the CS distribution in L483 is different from those in L1527 and TMC–1A (Sakai et al. 2014b, 2016; Oya et al. 2015), where CS resides only in the infalling–rotating envelope. Such a distribution of CS in L483 seems to resemble the IRAS 16293–2422 A case. In IRAS 16293–2422 A, the emission of the normal isotopic species of CS seems to come from the disk, as well as the infalling–rotating envelope (Y. Oya et al. 2017, in preparation), although the C^{34}S emission traces the envelope outside the centrifugal barrier (Favre et al. 2014). The difference of the behavior of CS would originate from the higher bolometric luminosity of L483 (13 L_{\odot}; Shirley et al. 2000).

Figure 11. PV diagrams of CS (J = 5–4), where the color maps are the same as in panels (c) and (d) of Figure 7. The black contours in panels (a) and (b) represent the results of the infalling–rotating envelope models, where \( M = 0.15 M_{\odot}, r_{CB} = 100 \) au, and \( i = 80^\circ \). The blue contours in panels (c) and (d) represent the results of the Keplerian model with the above \( M \) and \( i \) values, where the emission is simply assumed to come from the inside of the centrifugal barrier. In panels (a)–(d), the intrinsic line width is assumed to be 0.2 km s^{-1}, and the model image is convolved with the synthesized beam. The contour levels are every 20% from 5% of each peak intensity.
and IRAS 16293–2422 A (22 $L_\odot$; Crimier et al. 2010) than L1527 (1.7 $L_\odot$; Green et al. 2013) and TMC–1A (2.5 $L_\odot$; Green et al. 2013). The higher bolometric luminosity would cause the higher temperature of the disk component inside the centrifugal barrier, which prevents the CS depletion in this region. Since the binding energy of CS is 1900 K (UMIST Database for Astrochemistry; McElroy et al. 2013, http://udfa.ajmarkwick.net/index.php), the evaporation temperature is about 40 K (Yamamoto 2017). This is just above the midplane temperature of the disk just inside the centrifugal barrier in L1527 (30 K; Sakai et al. 2014a). If the midplane temperature inside the centrifugal barrier is higher in L483 owing to the higher bolometric luminosity, CS does not freeze out.

On the other hand, the rotation feature of the SO emission revealed in the PV diagram (Figure 9(a)) looks similar to that in L1527 (Sakai et al. 2014b), where SO mainly highlights the
centrifugal barrier. However, the high-velocity-shift components concentrated toward the protostar are much brighter in L483 than in L1527; hence, the rotation motion traced by SO in L483 is expected to come mainly from the disk component inside the centrifugal barrier (Figure 14). The relatively high bolometric luminosity in L483 could again help in escaping SO from depletion onto dust grains in the disk component.

Assuming that the SO emission appears inside the centrifugal barrier, we can directly estimate its radius. The deconvolved size (FWHM) is 0.5" (100 au) along the disk/envelope direction (P.A. = 15°); hence, the radius of the centrifugal barrier is estimated to be ~50 au. Since this size will be affected by the strong emission from the vicinity of the protostar, it can be regarded as the lower limit. On the other hand, the 5σ contour in the PV diagram of SO (Figure 9(a)) is extended to 2" 4 (≈480 au), where the radius deconvolved with the beam size along the P.A. of 15° is ~1" (≈200 au). Since the SO line may trace the envelope component just outside the

Figure 13. PV diagram of CS J = 5–4) along the direction perpendicular to the disk/envelope direction (P.A. = 105°), where the color maps are the same as in panel (d) of Figure 7. The black contours represent the results of the infalling–rotating envelope models. The parameters are M = 0.05, 0.15, and 0.5 M⊙; rcb = 0, 100, and 300 au; and i = 80°. The blue contours represent the results of the Keplerian model with the same physical parameters as those for the infalling–rotating envelope model in each panel. In the Keplerian model, the emission is simply assumed to come from the inside of the centrifugal barrier. The contour levels are every 20% from 5% of the peak intensity of each model.
centrifugal barrier (Sakai et al. 2017), this size can be regarded as the upper limit for the radius of the centrifugal barrier. Although it is difficult to derive the radius of the centrifugal barrier from the SO emission because of the contamination by the disk component in L483, these sizes will directly give rough estimates for the size of the centrifugal barrier. They are consistent with the estimate from the analysis of the PV diagrams of CS.

6. SiO Emission

The distribution of SiO extends to the northeastern direction from the continuum peak, as mentioned in Section 3. The P.A. of the direction of this extension is \(~\sim 35^\circ\) (Figure 4). Figure 16 shows the velocity channel maps of SiO. The blueshifted component of SiO (\(v_\text{LSR} < 5.2 \text{ km s}^{-1}\)) is offset from the protostar by \(0.5^\circ\) (\(\sim 100 \text{ au}\)), while the weak redshifted component appears at the protostar position. The position of
the blueshifted component of SiO is close to the expected position of the centrifugal barrier \( r_{CB} \sim 100 \text{ au} \) or inside of it. Since its velocity is faster than that of CS, it does not seem to come from a part of the infalling–rotating envelope. It is most likely that this component represents the shock caused by the outflow. The existence of such a shocked gas near the centrifugal barrier is puzzling. It might be related to the launching mechanism of the outflow, although the association of the shocked gas with the centrifugal barrier has to be explored at a higher angular resolution.

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Figure 16. Velocity channel maps of SiO \((J = 6–5; \text{color})\). Each map represents the averaged intensity with a velocity width of 1.4 km s\(^{-1}\). The white contours represent the 1.2 mm continuum map, where the contour levels are the same as those in Figure 2. The value in the top left corner of each panel is the averaged velocity (km s\(^{-1}\)).

7. Chemical Composition

L483 is proposed to have the WCCC character on the basis of the single-dish observations (Sakai et al. 2009a; Hirota et al. 2009, 2010; Sakai & Yamamoto 2013). It is confirmed by detection of CCH in the vicinity of the protostar at a 1000 au scale. Nevertheless, NH\(_2\)CHO and HCOOCH\(_3\), which are related to hot corino chemistry, are also detected. Furthermore, we tentatively detected the weak line of t-HCOOH. This is the first spatially resolved detection of saturated COMs in the WCCC source. Although such a mixed chemical character
source has been recognized as an intermediate source in previous studies (Sakai et al. 2009a), the present observation confirms its definitive existence of such a source at a high angular resolution.

The beam-averaged column densities of NH$_2$CHO and HCOOCH$_3$ toward the protostar position are evaluated by assuming local thermodynamic equilibrium at 70, 100, and 130 K (Table 2). This range of temperatures is typical of hot corinos (e.g., Oya et al. 2016). The beam-averaged column densities of NH$_2$CHO and HCOOCH$_3$ are calculated to be $(1.5 \pm 0.7) \times 10^{14}$ cm$^{-2}$ and $(7.0 \pm 4.0) \times 10^{13}$ cm$^{-2}$, respectively, at 100 K. The column densities change by 30% and 14% for the change in the assumed temperature by $\pm 30$ K for NH$_2$CHO and HCOOCH$_3$, respectively. The column density of the tentatively detected species (t-HCOOH) and the upper limits to the column densities of CH$_3$CHO and (CH$_3$)$_2$O are also calculated, as shown in Table 2.

To derive the fractional abundances relative to H$_2$, the beam-averaged H$_2$ column density is derived from the dust continuum to be $6.5 \times 10^{21}$ cm$^{-2}$ by using the following relation (Ward-Thompson et al. 2000):

$$N(H_2) = \frac{2 \ln 2 \cdot c^2}{\pi h c_m} \times \frac{F(\nu)}{\nu^3 \theta_{\text{major}} \theta_{\text{minor}}} \times \left(\exp\left(\frac{h \nu}{kT}\right) - 1\right),$$

(1)

where $M$ is the gas mass, $\kappa_\nu$ is the mass absorption coefficient with respect to the gas mass, $m$ is the average molecular mass (3.83 $\times$ 10$^{-24}$ g), $\nu$ is the frequency, $F(\nu)$ is the peak flux, $\theta_{\text{major}}$ and $\theta_{\text{minor}}$ are the major and minor beam size, respectively, $c$ is the speed of light, $h$ is Planck’s constant, and $T$ is the dust temperature. We here assume a dust temperature of 100 K. $\kappa_\nu$ is evaluated to be 0.008 cm$^2$ g$^{-1}$ at 1.2 mm with $\beta = 1.8$ (Shirley et al. 2011) under the assumption that $\kappa_\nu$ depends on the wavelength $\lambda$ with the equation $\kappa_\nu = 0.1 \times (0.3 \text{ mm}/\lambda)^{3/2}$ cm$^2$ g$^{-1}$ (Beckwith et al. 1990). If the dust temperature is 70 and 130 K, the H$_2$ column density is $9.5 \times 10^{23}$ and $4.9 \times 10^{23}$ cm$^{-2}$, respectively. The fractional abundances relative to H$_2$ are then evaluated to be $(1.3 - 3.9) \times 10^{-10}$ and $(7.3 - 16.2) \times 10^{-9}$ for NH$_2$CHO and HCOOCH$_3$, respectively, assuming that the gas temperature is the same as the dust temperature (Table 2).

These fractional abundances of NH$_2$CHO and HCOOCH$_3$ are comparable to those reported for the hot corinos, IRAS 16293–2422 (6 $\times$ 10$^{-10}$ and 9 $\times$ 10$^{-10}$; Jaber et al. 2014) and B335 (4 $\times$ 10$^{-10}$ and 5 $\times$ 10$^{-10}$; Imai et al. 2016). L483 indeed harbors a hot corino activity in the closest vicinity of the protostar.

As mentioned in Section 4, different molecules trace different parts in this source. The infalling–rotating envelope is traced by CS (and possibly CCH), while the compact component concentrated in the vicinity of the protostar, which is likely to be a disk component inside the centrifugal barrier, is traced by CS, SO, HNCO, NH$_2$CHO, and HCOOCH$_3$. Such a chemical change around the centrifugal barrier is previously reported for some other sources: L1527, TMC–1A, and IRAS 16293–2422 A (Sakai et al. 2014a, 2016; Oya et al. 2016). However, CS and SO are found to be quite abundant in the compact component concentrated in the vicinity of the protostar in this source, in contrast to the L1527 and TMC–1A cases. A situation similar to L483 is also seen in IRAS 16293–2422 A (Section 4.2). Thus, the chemical change would be highly dependent on sources. Hence, it is still essential to investigate chemical structures of various protostellar sources at a subarcsecond resolution.

8. Summary

We observed the Class 0 protostar L483 with ALMA in various molecular lines. The major results are as follows:

(1) A chemical differentiation at a 100 au scale is found in L483. The CCH emission has a central hole of 0.5 arcsec (100 au) in radius. The CS emission traces the compact component concentrated near the protostar, the extended envelope component, and a part of the outflow cavity. In contrast, the SO and HNCO emission only shows the compact component concentrated in the vicinity of the protostar in this source, in contrast to the L1527 and TMC–1A cases. A situation similar to L483 is also seen in IRAS 16293–2422 A (Section 4.2). Thus, the chemical change would be highly dependent on sources. Hence, it is still essential to investigate chemical structures of various protostellar sources.

(2) In spite of the WCCC character of this source, the saturated COMs, NH$_2$CHO and HCOOCH$_3$, are detected. Their emission is highly concentrated near the protostar. This result is the first spatially resolved example of the mixed character source of WCCC and hot corino chemistry.

(3) The kinematic structures of the envelope and the disk components traced by CS are analyzed by simple models of the infalling–rotating envelope and the Keplerian disk in order to understand the observed chemical differentiation.
in terms of the physical structure. The protostellar mass of 0.1–0.2 \( M_\odot \) and the radius of the centrifugal barrier of 30–200 au roughly explain the infalling–rotating envelope part of the observed PV diagrams of CS. The compact component of the observed PV diagrams of CS. The compact component shows the Keplerian disk component inside the centrifugal barrier, although the rotation curve is not resolved. Hence, the above chemical change seems to be occurring around the centrifugal barrier.

(4) In L483, CS, which is thought to be a good tracer of the infalling–rotating envelope, traces the disk component as well. SO, which highlights the ring structure around the centrifugal barrier in L1527 and TMC–1A, also traces the disk component in this source. These results would originate from the higher luminosity of L483.

(5) The SiO distribution has an extension from the protostar position. It may trace the local outflow shock near the centrifugal barrier.

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