Extremely High Excitation SiO Lines in Disk-outflow Systems in Orion Source I

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Abstract

We present high-resolution images of the submillimeter SiO line emissions of a massive young stellar object Orion Source I using the Atacama Large Millimeter/submillimeter Array at band 8. We detected the 464 GHz SiO ν = 4 J = 11–10 line in Source I, which is the first detection of the SiO ν = 4 line in star-forming regions, together with the 465 GHz 29SiO ν = 2 J = 11–10 and the 428 GHz SiO ν = 2 J = 10–9 lines with a resolution of 50 au. The 29SiO ν = 2 J = 11–10 and SiO ν = 4 J = 11–10 lines have compact structures with a diameter of <80 au. The spatial and velocity distributions suggest that the line emissions are associated with the base of the outflow and the surface of the edge-on disk. In contrast, SiO ν = 2 J = 10–9 emission shows a bipolar structure in the direction of northeast–southwest low-velocity outflow with a ~200 au scale. The emission line exhibits a velocity gradient along the direction of the disk elongation. With the assumption of the ring structure with Keplerian rotation, we estimated the lower limit of the central mass to be 7 M⊙ and the radius to be 12 au < r < 26 au.

Key words: ISM: individual objects (Orion KL) – radio continuum: stars – stars: individual (Orion Source I) – stars: formation

1. Introduction

Orion Source I is a high-mass protostar candidate located in the Orion Kleinmann-Low (KL) region (Kleinmann & Low 1967). Source I is thought to have a high-luminosity of >10⁸ L⊙; however, it is so highly embedded that it cannot be observed directly at optical and infrared wavelengths. Due to its proximity (D ≈ 420 pc; Hirota et al. 2007; Menten et al. 2007; Kim et al. 2008), Source I has been studied in detail via the high-resolution observations with radio and submillimeter wavelengths.

The source is associated with a low-velocity (V ≈ 18 km s⁻¹) bipolar outflow with a size of ~1000 au along the northeast–southwest direction (Plambeck et al. 2009; Zapata et al. 2012; Greenhill et al. 2013). The radio continuum observations with the Very Large Array and Atacama Large Millimeter/submillimeter Array (ALMA) have imaged the elongated continuum emission at the center of the outflow, which is consistent with an edge-on disk perpendicular to the bipolar outflow (Reid et al. 2007; Goddi et al. 2011; Hirota et al. 2015; Plambeck & Wright 2016; Orozco-Aguilera et al. 2017). The bright SiO maser emission, which is rare in the star-forming regions, has been found toward Source I.

The high-resolution observations with VLBI revealed that the 43 GHz ν = 1 and 2 J = 1–0 SiO maser spots are distributed in an X-shaped region with a size of ~100 au (Greenhill et al. 1998; Kim et al. 2008; Matthews et al. 2010; Issaoun et al. 2017). The observations revealed that the masers have a stable velocity gradient in the direction parallel to the elongation of the radio continuum, while moving outward along the arms of the X-shape. These behaviors suggest that the masers are associated with the rotating outflow from the surface of the disk. Recent ALMA observations detected high-frequency lines of H₂O, CO, and silicon- and sulfur-rich molecules at the position of Source I (e.g., Hirota et al. 2012, 2014, 2016a, 2017; Plambeck & Wright 2016; Ginsburg et al. 2018), which are tracing the disk and the outflowing gas from the disk. The velocity structure of the high-frequency lines also shows the rotational feature similar to those of the 43 GHz ν = 1 and 2 SiO masers. The observed velocity gradients can be modeled with a Keplerian rotation curve with the enclosed mass of ~5–9 M⊙. (Kim et al. 2008; Matthews et al. 2010; Hirota et al. 2014; Plambeck & Wright 2016; Hirota et al. 2017). More recently, Ginsburg et al. (2018) reported the continuum and spectral line emission from Source I’s disk and outflow with the ALMA observation at a resolution of 0.03–0.06. They detected the continuum and several unidentified line emissions in the disk, as well as a thermal H₂O 5_{2,0}–0_{4,3} line tracing the upper and lower boundaries of the disk. The kinematics and morphology of the continuum and the line emission confirmed the idea of rotating outflow from the disk suggested in the previous studies, although they obtained the higher central mass of ~15 M⊙.

The high-resolution observations of the masers and the high-frequency line emissions reveal a rotating, wide-angle inner outflow and a perpendicular disk around Source I, which can be explained by magnetocentrifugal disk wind launched by the central high-mass young stellar object (e.g., Matthews et al. 2010; Greenhill et al. 2013; Hirota et al. 2017). This picture is similar to the low-mass star formation scenario, which describes the transfer of mass and angular momentum between the accretion disk and outflows (Vaidya & Goddi 2013; Hirota et al. 2017). Besides, the ALMA observations with CH₃CN and CH₃OH lines revealed the signature of the infall motion toward Source I, which also supports the star formation via accretion.
Table 1

| Frequency (MHz) | Molecule | Transition | $E_i$ (K) |
|-----------------|----------|------------|-----------|
| 465014.010      | $^{29}$SiO | $v = 2, 11-10$ | 3611      |
| 428087.451      | SiO      | $v = 2, 10-9$  | 3614      |
| 464244.956      | SiO      | $v = 4, 11-10$ | 7086      |

Note. Line information is taken from the Cologne Database for Molecular Spectroscopy (CDMS; Müller et al. 2005). $E_i$ is the lower state energy.

We successfully detected 465 GHz $^{29}$SiO $v = 2 J = 11-10$, 464 GHz SiO $v = 4 J = 11-10$, and 428 GHz SiO $v = 2 J = 10-9$ lines toward Source I. In particular, this is the first time the SiO $v = 4 J = 11-10$ line has been detected in star-forming regions. The SiO $v = 4$ transition has been detected toward a red supergiant VY CMa at the $J = 5-4$ transition at 211 GHz for the first time (Cernicharo et al. 1993). Recently, owing to the high spectral resolution and the sensitivity of ALMA, SiO emission with the higher vibrational excitation level has been observed in late-type stars (Decin et al. 2018; Kervella et al. 2018). Decin et al. (2018) detected the SiO $v = 4$ and $5 J = 8-7$ line (R Dor and IK Tau) and the Si$^{18}$O $v = 5 J = 9-8$ line (IK Tau) in AGB stars, and Kervella et al. (2018) observed the SiO $v = 6$ and $7 J = 8-7$ line in a red supergiant Betelgeuse.

Figure 1 displays the observed SiO line spectra summed over $0.024 \times 0.024$ boxes centered on the continuum peaks. The velocities of the emissions range from $\sim-30$ km s$^{-1}$ to $\sim30$ km s$^{-1}$ and generally are centered on $V_{lsr} \sim 5$ km s$^{-1}$, which is the systemic velocity of Source I (Plambeck et al. 1990). The $^{29}$SiO $v = 2 J = 11-10$ and SiO $v = 4 J = 11-10$ emission show double-peak profiles with peak velocities at $\sim-5$ km s$^{-1}$ and $\sim15$ km s$^{-1}$, which are similar to those of other high-frequency lines and masers (Kim et al. 2008; Hirota et al. 2012, 2014, 2016a, 2017; Matthews et al. 2010; Greenhill et al. 2013; Ginsburg et al. 2018).

The SiO $v = 2 J = 10-9$ line spectrum also shows the double-peak profile, but the velocity of the blueshifted emission peak is shifted by $\sim5-10$ km s$^{-1}$ from those of other emission lines. Also, the SiO $v = 2 J = 10-9$ line appears in absorption at the velocity range of $-25 < V_{lsr} < -10$ km s$^{-1}$. The self-calibration and the synthesized imaging were carried out using the CASA software package. The details of the data analysis are summarized in Hirota et al. (2016b, 2017). The synthesized images of each velocity channels were made for all lines by using the CASA task clean with uniform weighting. The synthesized beam sizes were $0''13 \times 0''11$ with a position angle of $82^o$ for the 465 GHz $^{29}$SiO $v = 2 J = 11-10$ line, $0''12 \times 0''11$ with a position angle of $87^o$ for the 464 GHz SiO $v = 4 J = 11-10$ line, and $0''09 \times 0''07$ with a position angle of $82^o$ for the 428 GHz SiO $v = 2 J = 10-9$ line. We made the moment maps using the CASA task immoments. To make a position centroid map of the line emission, we did a two-dimensional Gaussian fitting to each velocity channel map using the task JMFIT with the AIPS software package. As discussed in Hirota et al. (2016b), the continuum peak positions at different frequencies deviate from each other by 100 mas at maximum for astrometric calibration errors in the observations or data analysis. Thus, we did not use the absolute position of the emissions in comparing the maps at different frequency bands in this paper.

3. Results

3.1. Spectral Profile

Observations were executed on August 27 (460 GHz) and September 22 (430 GHz) in 2015 with ALMA as one of the science projects in cycle 2 (ADS/JAO.ALMA#2013.1.00048.S). Details of observations are summarized in Hirota et al. (2016b, 2017). The tracking center position of the target source was R.A. (J2000) $= 05^h35^m14^s512$, decl. (J2000) $= -05^\circ 22' 30'' 57'$. The total on-source integration times of the target source were 458 s and 2065 s for 460 GHz and 430 GHz, respectively. The line information presented in this paper is summarized in Table 1. For the observations at both 430 and 460 GHz, a primary flux calibrator was J0423$-$013 and a bandpass calibrator was J0522$-$3627. The secondary gain calibrators were J0607$-$0834 for 460 GHz observations and J0501$-$0159 for 430 GHz observations. The array was composed of 40 and 35 antennas with maximum baseline lengths of 1575 m and 2270 m at 460 GHz and 430 GHz, respectively. The average system noise temperature was $\sim300$ K at 460 GHz and $500$ K at 430 GHz. The spectral window centered at 428.0 GHz and 464.6 GHz included observed SiO line emissions. The total bandwidth of the spectral bands was 1875 MHz, and the channel spacing was 976.562 kHz, corresponding to the velocity resolution of $\sim0.6$ km s$^{-1}$. On the other hand, the proper motion measurements of young stellar objects in Orion KL suggested that dynamical interactions between massive stars played a role in the evolution of Source I (Rodríguez et al. 2005; Bally et al. 2011; Goddi et al. 2011; Rodríguez et al. 2017). The scenarios suggest that the dynamical decay of a multiple-star system, which consist of BN, Source I, and source n, occurred $\sim500$ yr ago, and released gravitational energy during the interaction would have triggered the explosive outflow seen in H$_2$ and CO. The scenarios expect the Source I to be a $\sim20 M_\odot$ binary system (Bally et al. 2011; Goddi et al. 2011; Rodríguez et al. 2017). The mass of Source I reported by Ginsburg et al. (2018) of 15 $M_\odot$ is more consistent with these scenarios than those of previous values, although there are still controversies about the detailed process (Chatterjee & Tan 2012; Luhman et al. 2017).

The study of the physical properties of Source I requires information of the inner outflow/disk region with higher-resolution observations. Toward this goal, the high excitation transition lines could be a potential tool to investigate the hot and dense gas near the protostar (Hirota et al. 2014, 2017; Plambeck & Wright 2016; Ginsburg et al. 2018). In this paper, we present the results of ALMA observations at 0$''$1 resolution to study dynamical properties of the disk-outflow system in close vicinity to Source I. The observation yields the maps of SiO lines with the excitation temperature of 3600–7000 K, which traces the inner part of the disk-outflow system of Source I.
It is unlikely to be explained by a self-absorption because the SiO $v = 2$ $J = 10–9$ line has a high excitation temperature of $E_I \sim 3600$ K, and they would be located very close to the central star. A possible candidate for the absorption line is the SO $v = 0$ $9_{10} - 8_{0}$ at 428110.747 MHz ($E_I = 100$ K), which has a velocity of $v \sim 1$ km s\(^{-1}\) at the absorption peak. In Orion KL, SO emission is detected in the hot core and the compact ridge gas, as well as the disk and outflow near Source I (Wright et al. 1996; Plambeck & Wright 2016). However, the velocity of the gas in the hot core and the compact ridge is 2–11 km s\(^{-1}\). Thus, the absorption is likely to be associated with the SO in the outflow. Plambeck & Wright (2016) also reported the asymmetric absorption limited to blueshifted velocities ($-13 < V_{\text{lsr}} < 5$ km s\(^{-1}\)) in molecular lines with upper state energies $E_U < 500$ K, especially in the sulfur-bearing species. They also suggested that the absorption could be associated with material within the outflow of Source I because the velocity width of the absorption corresponds to the half-width of other lines associated with the outflow.

### 3.2. Spatial Structure

Figure 2 displays the integrated intensity and peak velocity maps of SiO emissions overlaid with the continuum emission at 430 GHz and 460 GHz. In Figures 2(b) and (c), $^{29}$SiO $v = 2$ $J = 11–10$ and SiO $v = 4$ $J = 11–10$ emissions exhibit the compact structures centered on Source I with deconvolved sizes of $0.013 \times 0.013$ and $0.008 \times 0.006$, respectively. Both lines show the velocity gradient along the northwest–southeast direction, which is similar to $v = 1$ and $2$ $J = 1–0$ SiO masers (Kim et al. 2008; Matthews et al. 2010) and H\(_2\)O emission (Hirota et al. 2014, 2017). It is clear that the $v = 4$ transition with the highest excitation energy level arises at the smallest radii from the YSO, where high temperatures are expected. In contrast to the elongated structure of the continuum emission, the $^{29}$SiO $v = 2$ $J = 11–10$ and SiO $v = 4$ $J = 11–10$ emissions show almost circular structure. Besides, it seems that the peak positions of both SiO lines are slightly offset to the northeast direction from the peak position of the continuum emission. This result is consistent with the previous ALMA...
observations reporting that the molecular line emission is offset from the disk midplane (Plambeck & Wright 2016; Ginsburg et al. 2018). Plambeck & Wright (2016) reported that line emissions such as SiS are spatially extended relative to the continuum. Also, Ginsburg et al. (2018) separated the line-emitting region from the continuum emission with higher angular resolution and reported that the SiO and H$_2$O lines are seen in the region below and above the continuum emission. It suggests that the continuum emission is most likely optically thick emission from the disk and molecular line emissions originate from the atmosphere of the disk and/or the base of the outflow.

The peak flux densities of $^{29}$SiO $v = 2 J = 11–10$ and SiO $v = 4 J = 11–10$ lines are 1.3 Jy and 1.2 Jy at the LSR velocity of $−4.3$ km $s^{-1}$ and $−6$ km $s^{-1}$, respectively. We measured the source size of each channel as $0″2 \times 0″16$ and $0″15 \times 0″13$ with the two-dimensional Gaussian fitting to the channel maps. Using measured flux densities and the source sizes, the brightness temperatures of $^{29}$SiO $v = 2 J = 11–10$ and SiO $v = 4 J = 11–10$ lines are estimated to be $229$ K and $349$ K. The estimated brightness temperatures are lower than the temperature of the dust ($500–800$ K) and the gas ($1000–2000$ K; Goddi et al. 2009; Hirota et al. 2016b; Plambeck & Wright 2016). One possible explanation is that SiO lines are optically thin thermal emission.

On the other hand, we cannot exclude the possibility of the maser nature of the $^{29}$SiO $v = 2 J = 11–10$ and SiO $v = 4 J = 11–10$ lines because of the similarity with other maser transitions, such as the small distribution comparable to the 43 GHz $v = 1$, $2 J = 1–0$ masers, and the high density/temperature in this region. From the spectral energy distribution, Plambeck & Wright (2016) inferred a disk mass of $0.02–0.2 M_⊙$ and $n_H > 3.2 \times 10^{10}$ cm$^{-3}$. The existence of SiO $v = 1$ and $2 J = 1–0$ masers also suggests that the temperature and the density at the disk surface must be $1000–2000$ K and $10^{10.5}$ cm$^{-3}$ (Goddi et al. 2009).

In the model calculation for the excitation of the SiO $v = 4 J = 5–4$ maser presented for VY CMa (Cernicharo et al. 1993), the pumping of the SiO $v = 4$ maser requires the local density of $\sim 0.5–5 \times 10^{10}$ cm$^{-3}$ at the gas temperature of $1500$ K. Although the physical properties of the SiO maser-emitting region in a late-type star would be different from those in Source I, the disk properties of Source I are hot and dense enough to pump even a $v = 4$ SiO maser. In this case, the estimated brightness temperatures of $229$ K and $349$ K would be the lower limits, considering the possibility that the compact maser emission is unresolved.

In Figure 2(a), the SiO $v = 2 J = 10–9$ emission exhibits a bipolar structure centered on a Source I size of $\sim 0′′5 \times 0′′5$, which is also visible in images of the low-velocity northeast–southwest outflow traced by SiO and H$_2$O lines including several maser lines (e.g., Plambeck et al. 2009; Niederhofer et al. 2012; Greenhill et al. 2013; Hirota et al. 2017). The moment 1 map clearly shows the velocity gradient in the northwest–southwest direction, and it is consistent with that of the outflow with the size of $<5''$ (Kim et al. 2008; Greenhill et al. 2013; Hirota et al. 2017). The moment 0 map indicates that the redshifted emission of the SiO $v = 2 J = 10–9$ line is dominant over the blueshifted emission. This trend is also seen in the 658 GHz and 321 GHz H$_2$O lines (Hirota et al. 2014, 2016a), which trace the base of the outflow from the rotation disk around Source I. We confirmed that the absorption of the blueshifted emission is located at the southeast part of the bipolar structure. It supports the idea that the material within the outflow or the disk of Source I results in the absorption feature (Plambeck & Wright 2016).

4. Discussion

4.1. Comparison with SiO $v = 1$ and $2 J = 1–0$ masers

Our results show that the size of the spatial distributions and the velocity ranges of high-frequency SiO emission are consistent with those of SiO $v = 1$ and $2 J = 1–0$ masers. To compare the distributions between the different SiO lines, we calculated the relative positions of SiO $v = 1$ and $2 J = 1–0$ masers toward the position of Source I using the absolute positions measured by Kim et al. (2008) and Goddi et al. (2011). Then, we overlaid the maps registering the peak position of the continuum emissions to the position of Source I. Figure 2(a) shows the positions of the $v = 1$ and $2 J = 1–0$ SiO masers superposed on the moment map of the SiO $v = 2 J = 10–9$ line and the $430$ GHz continuum emission. It reveals that the X-shaped distribution of SiO $v = 1$ and $2 J = 1–0$ masers is well consistent with the base of the bipolar structure of SiO $v = 2 J = 10–9$ emission, as well as the upper and lower boundary of the continuum emission. This result confirms the idea that the SiO $v = 2 J = 10–9$ line traces the base of rotating outflow driven by the magnetocentrifugal disk wind launched by a central star (Hirota et al. 2017).

To evaluate the detailed structure of the SiO $v = 4 J = 11–10$ and $^{29}$SiO $v = 2 J = 11–10$ emission, we made position centroid maps by performing two-dimensional Gaussian fitting to each velocity channel maps. Figure 3 displays the position centroids of the $v = 1$ and $2 J = 1–0$ SiO maser, SiO $v = 4$, and $^{29}$SiO $v = 2 J = 11–10$ emissions. With the synthesized beam size and signal-to-noise ratio at the peak velocity channel of each line, the positional accuracy was as high as $\sim 1$ mas for the $v = 4 J = 11–10$ line and $\sim 2$ mas for the $v = 2 J = 11–10$ line. The results demonstrate the offset of the $v = 4 J = 11–10$ line and $^{29}$SiO $v = 2 J = 11–10$ emissions from the disk midplane, as also seen in Section 3.2. While Ginsburg et al. (2018) resolved the molecular line emission from above and below the disk, we could not detect the emission in the southwest of the disk, possibly due to the lower sensitivity and resolution.

The $^{29}$SiO $v = 2 J = 11–10$ emission is mainly found between the eastern and northern arms of the X-shape and also in the vertical structures from the disk, such as blueshifted emission along the eastern arm and high-velocity components near the disk midplane. It confirms that the $^{29}$SiO $v = 2 J = 11–10$ emission traces the rotating outflow as other SiO line emission (e.g., Plambeck & Wright 2016; Hirota et al. 2017; Ginsburg et al. 2018). On the other hand, the $v = 4 J = 11–10$ emission is only found in a line connecting the base of eastern and northern arms of $43$ GHz $^{29}$SiO masers, which resembles the H$_2$O emission in Ginsburg et al. (2018). The morphology and velocity gradient of this line suggests that it traces both the surface of the disk and the base of the outflow.

4.2. The Kinematics of $v = 4 J = 11–10$ Line Emission

Figure 4 shows the position–velocity diagrams of the SiO $v = 4 J = 11–10$ and $^{29}$SiO $v = 2 J = 11–10$ emissions along the axis with the position angle of $140°$ (Hirota et al. 2014). The spatial distribution and the velocity gradients along the major axis of the continuum emission indicate that the SiO $v = 4 J = 11–10$...
emission is related to the rotating disk. However, the absence of the high-velocity components at the central position suggests that the high-frequency SiO line emissions are associated with a rotating ring structure rather than a filled disk. To find the parameters of the ring structure, we fit the observed rotation curve with a simulated rotation curve using a simple model similar to those of Hirota et al. (2014) and Plambeck & Wright (2016). We assumed a thin, edge-on ring structure in Keplerian rotation around a central star. In each position, the gas with uniform temperature and density emit the optically thin emission. The thermal width of 3 km s\(^{-1}\) was assumed. We set the systemic velocity of 6 km s\(^{-1}\), which is the central value of the observed velocity range. We simulated the rotation curve for a range of inner radii \(r_{\text{in}}\) and outer radii \(r_{\text{out}}\) with central masses ranges of 5 to 15 \(M_\odot\). As a result, we assess that \(r_{\text{in}} = 12\) au, \(r_{\text{out}} = 26\) au, and a central mass of 7 \(M_\odot\) for the best parameter.

Figure 4(b) presents the results of the fitting to the velocity centroids of the SiO \(v = 4\) \(J = 11–10\) emission. We also display the rotation curves with central masses of 5, 10, and 15 \(M_\odot\). The rotation curves for smaller masses also seem to fit with the observed rotation curve near the systematic velocity, but it could not reproduce the high-velocity components at the innermost radii. In contrast, a simulation with a higher mass requires smaller inner radii and larger outer radii to fit the observed rotation curve. However, we cannot exclude the possibility of the higher central mass because we did not consider the offset from the disk midplane and the effect of the outflow. Also, it is possible that the spatial resolution and sensitivity of our observation was not enough to detect the detailed structure near the inner and outer radii. Thus, we notice again that the mass of 7 \(M_\odot\) is a lower limit of the mass of Source 1.

The estimated mass of 7 \(M_\odot\) is consistent with those derived by Plambeck & Wright (2016) and Hirota et al. (2014), as well as the mass estimated with 43 GHz SiO masers (Matthews et al. 2010). The velocity gradient of the \(v = 1\) and 2 SiO masers supports the rotating structure with an enclosed mass of \(~7–8\) \(M_\odot\) (Kim et al. 2008; Matthews et al. 2010). The rotation curve of 336 GHz H\(_2\)O and 340 GHz molecular lines also suggests the rotating ring with a central mass of \(~5–7\) \(M_\odot\) (Hirota et al. 2014; Plambeck & Wright 2016). Also, Hirota et al. (2017) suggested the mass of Source 1 to be 8.7 \(M_\odot\) with the rotation of the Si\(^{18}\)O \(J = 12–11\) emission.

On the other hand, recent ALMA observation with a resolution <0.06 detected 232 GHz H\(_2\)O lines tracing the X-shape distribution of SiO \(v = 1\) and 2 \(J = 1–0\) masers (Ginsburg et al. 2018). Using the outer edge of the position–velocity diagram, they estimated a mass of Source 1 of \(>15 \pm 2\) \(M_\odot\), which is twice that of the previous estimations and the result of this observation. This inconsistency could be caused by the fact that we missed a faint emission at the high-velocity component near the central source due to the insufficient resolution and sensitivity. Also, because our model based on the emission centroids samples only the peak positions at the position–velocity diagram, it gives a lower mass compared with the case using the highest velocity at a certain position as Ginsburg et al. (2018) does.

Figure 4(a) displays the position–velocity diagram of the SiO \(v = 4\) \(J = 11–10\) emission. We could not fit the data with the Keplerian rotation curve because the power-law profile is not clear in our PV diagram, so we overlaid the Keplerian rotation curve with 10 and 15 \(M_\odot\). It also shows the possibility that the estimated mass can be modified if we can confine the velocity structure more precisely. Future observations with a higher resolution and sensitivity are required to constrain the central mass with the kinematics in this scale.

Although the resolution of our observation is not enough to resolve the issue on the mass estimation of Source 1, our observation shows that the SiO \(v = 4\) \(J = 11–10\) emission traces the small region with a radius <30 au tracing the disk surface and the inner outflow. Their high excitation level and the compact distribution implies that SiO \(v = 4\) \(J = 11–10\) emission is a promising tracer for studying the kinematics of the innermost region where the outflow is launching with higher-resolution observations in the future.

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**Figure 3.** (a) Peak positions of the SiO \(v = 1\) and 2 \(J = 1–0\) maser emission (gray circle) and the SiO \(v = 4\) \(J = 11–10\) emission (colored circle). (b) Peak positions of the SiO \(v = 1\) and 2 \(J = 1–0\) maser emission (gray circle) and \(^2\)SiO \(v = 2\) \(J = 11–10\) emission (colored cross). The color of the SiO \(v = 4\) and \(^2\)SiO \(v = 2\) emission represents the line-of-sight velocity. The cross at (0, 0) corresponds to the position of Source I (Goddi et al. 2011).
The dashed green line represents the Keplerian rotation curve with overlaid the model curves of JAO.ALMA. Figure 4. The Astrophysical Journal, of (operated by ESO, AUI the Republic of Chile. The Joint ALMA Observatory is supported by the ALMA Japan Research Grant of M.K.K. was supported by the ALMA Japan Research Grant of MEXT/JSPS KAKENHI. K.M. is supported by the MEXT/JSPS KAKENHI grant numbers 24540242 and 25120007. Data analysis was in part carried out on the common use data analysis computer system at the Astronomy Data Center, ADC, of NAOJ.

Facility: ALMA.

4.3. Summary

We observed the SiO line around Source I with a resolution of ~0″1 and found the following:

1. We detected SiO ν = 4 J = 11–10 line near Source I. This is the first detection of SiO ν = 4 emission in the star-forming regions. Besides, the nature of the emission will enable us to trace the inner part of the disk/outflow system of Source I using observations with a higher resolution in the future.

2. SiO ν = 2 J = 10–9 emission shows the bipolar distribution with a size of 0″5 × 0″5, tracing the base of the northeast–southwest outflow from Source I, while the 29SiO ν = 2 and SiO ν = 4 J = 11–10 lines show the compact distribution tracing the surface of the disk and the base of the outflow of Source I.

3. The centroids of the velocity distribution of the SiO ν = 4 J = 11–10 line suggest that the emission traces the ring structure with 12 au < r < 26 au and a central mass of 7.1 M_☉. The estimated value would be a lower limit of the mass because the sensitivity and resolution of our observation are not enough to resolve the faint components in the rotation curve.

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