A HOT MOLECULAR CIRCUMSTELLAR DISK AROUND THE MASSIVE PROTOPSTAR ORION SOURCE I

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Accepted 2013 December 1; accepted 2014 January 22; published 2014 February 3

ABSTRACT

We report new Atacama Large Millimeter/Submillimeter Array (ALMA) observations of a circumstellar disk around Source I in Orion KL, an archetype of massive protostar candidates. We detected two ortho-H$_2$O lines at 321 GHz (10$_{2,9}$–9$_{3,6}$) and 336 GHz (7–8) for the first time in Source I. The latter one is in a vibrationally excited state at the lower energy level of 2939 K, suggesting evidence of hot molecular gas close to Source I. The integrated intensity map of the 321 GHz line is elongated along the bipolar outflow while the 336 GHz line map is unresolved with a beam size of 0.4″. Both of these maps show velocity gradients perpendicular to the bipolar outflow. The velocity centroid map of the 321 GHz line implies a spatial and velocity structure similar to that of vibrationally excited SiO masers tracing the root of the outflow emanating from the disk surface. In contrast, the 336 GHz line is most likely emitting from the disk midplane with a diameter of 0.7″ (84 AU) as traced by radio continuum emission. The observed velocity gradient and the spectral profile of the 336 GHz H$_2$O line can be reconciled with a model of an edge-on ring-like structure with an enclosed mass of $>7 M_\odot$ and an excitation temperature of $>3000$ K. The present results provide further evidence of a hot and neutral circumstellar disk rotating around Source I with a diameter of $\sim 100$ AU scale.

Key words: ISM: individual objects (Orion KL) – ISM: molecules – radio lines: ISM – stars: individual (Source I)

1. INTRODUCTION

While it is well understood how low-mass solar-type stars form, the formation process of massive stars remains to be addressed. Recent observations of massive young stars suggested the existence of circumstellar disks (Patel et al. 2005; Jiang et al. 2005; Kraus et al. 2010), which favors formation via disk accretion rather than via other processes such as stellar collisions (Bally & Zinnecker 2005). However, the physical characteristics of accretion disks, especially at a scale of $\sim 100$ AU, are still debatable, mainly due to limited spatial resolution.

Because of its proximity to the Sun at a distance of 420 pc (Menten et al. 2007; Kim et al. 2008), Orion KL (a Kleinman–Low object) has been recognized as one of the best laboratories in which to study massive star-formation processes. Among a number of young stars, a radio source called Source I is prominent in this region and is thought to have a high luminosity of $>10^4 L_\odot$ (Menten & Reid 1995). It is the driving source of a bipolar outflow along the northeast–southwest direction with a scale of 1000 AU (Wright et al. 1995; Zapata et al. 2012; Niederhofer et al. 2012; Greenhill et al. 2013), which seems consistent with the base of a larger scale high-velocity outflow traced by near-infrared shocked H$_2$ emission (Allen & Burton 1993; Bally et al. 2011). For this reason, it has sometimes been interpreted as a radio jet oriented in the northwest–southeast directions (Testi et al. 2010; Chatterjee & Tan 2012).

Furthermore, there are continued discussions related to the mass of Source I. A rotation curve of the vibrationally excited 43 GHz SiO masers indicates an enclosed mass of $>7 M_\odot$ (Kim et al. 2008; Matthews et al. 2010). The near-infrared reflected spectrum can be explained by emission from a circumstellar disk around a 10 $M_\odot$ protostar (Testi et al. 2010). However, it has also been claimed that Source I consists of a massive binary system with a total mass of 20 $M_\odot$, given the dynamics of the region including Source I and a BN (Becklin–Neugebauer) object (Gómez et al. 2008; Bally et al. 2011; Goddi et al. 2011), although these dynamical scenarios are still controversial (Chatterjee & Tan 2012).

The physical properties of the associated disk are also under debate (Reid et al. 2007; Testi et al. 2010; Bally et al. 2011; Goddi et al. 2011; Okumura et al. 2011; Plambeck et al. 2013; Sitarski et al. 2013), and these properties are crucial to understanding the mechanism of massive star formation. Further observations of Source I are essential to enable an understanding of not only its origin but also the formation mechanisms of massive stars in general. For this purpose, we present the observational results of submillimeter H$_2$O lines detected in Source I with the newly constructed Atacama Large Millimeter/Submillimeter Array (ALMA).

2. OBSERVATIONS

Observations were carried out with ALMA on 2012 July 16, August 25, and October 21. The target source was Orion KL and the tracking center position was taken to be the
bursting 22 GHz H$_2$O maser. R.A.(J2000) = 05$^h$35$^m$14$^{s}$.125, decl.(J2000) = $-05^\circ$22'36"486 (Hirota et al., 2011), which is 7" southwest of Source I. The on-source integration time was about 100 s for each session. The array consisted of 21–28 antennas with a diameter of 12 m each in the extended configuration with a maximum baseline length of 400 m. A primary flux calibrator, band-pass calibrator, and secondary gain calibrator were Callisto, J053851-440507/J0423-013, and J0607-085, respectively.

Two ortho-H$_2$O lines at 321.225656 GHz (10$_2$–9$_3$,6) and 336.227931 GHz (9$_2$–8$_3$,6) were observed simultaneously. The 336 GHz H$_2$O line lies in the excited state in bending mode ($v_2 = 1$). The lower state energy levels are 1846 K and 2939 K for the 321 GHz and 336 GHz H$_2$O lines, respectively (Chen et al. 2000). The ALMA correlator provided four spectral windows, each with a bandwidth of 468.750 MHz. The channel spacing of the spectrometers was 122 kHz. The system noise temperature ranged from 100 to 200 K, depending on the observing frequency and weather conditions.

3. DATA REDUCTION

Synthesis imaging and self-calibration were done with the CASA software package. We set a velocity resolution of 0.125 km s$^{-1}$ (which corresponds to 130–140 kHz resolution) in the synthesized imaging of the H$_2$O lines. First, both phase and amplitude self-calibrations were done using the continuum emission of Orion KL by integrating over line-free channels. The peak intensity and rms noise level of the continuum emission was 698 mJy beam$^{-1}$ and 9 mJy beam$^{-1}$, respectively.

The self-calibration solutions were applied to all the spectral channels including the target H$_2$O lines. We compared the continuum emission and selected spectral lines of methyl formate, HCOOCH$_3$, to check the stability of the observed flux scale. As a result, we found a possible variation in the continuum and line intensities between different observing sessions. This variation is most likely due to different array configurations which could result in different degrees of missing flux for extended emission features. In contrast, we did not find significant flux variation in the 321 GHz and 336 GHz H$_2$O lines as shown in Figure 1. This suggests that the H$_2$O lines are emitting from a compact source and have no intrinsic time variation unlike the circumstellar 321 GHz H$_2$O masers around late-type stars (Yates & Cohen 1996). Considering these results, we estimated the accuracy of flux measurements to be $\sim$20%.

In order to obtain higher spatial resolution and to exclude the contribution from the extended emission component, we produced synthesized images of the 321 GHz and 336 GHz H$_2$O lines as well as the continuum emission by using the uniform-weighted visibility data with a UV distance longer than 200 k$''$. The resultant beam size is 0$''$.40 $\times$ 0$''$.34 with a position angle of 60$^\circ$. The image rms noise level was $\sim$30 mJy beam$^{-1}$ at each channel. Because these maps are free from the sidelobes caused by strong extended emission, the noise levels are improved compared with those of full UV sampling images.

4. RESULTS

We detected two H$_2$O lines at 321 GHz and 336 GHz toward Source I (Figure 1). Although the 321 GHz line has been detected in star-forming regions (Menten et al. 1991; Patel et al. 2007), the vibrationally excited 336 GHz line has been detected only in a red supergiant such as VY CMa (Menten et al. 2006). Thus, this is the first detection of the 336 GHz H$_2$O line in star-forming regions. Along with another vibrationally excited H$_2$O line at 232 GHz, newly detected with ALMA (Hirota et al. 2012), these transitions will be unique tracers of massive young stars. Both of the 321 GHz and 336 GHz emissions are concentrated in the vicinity of Source I. Because of their high excitation energy levels, these lines clearly suggest a hot molecular gas associated with Source I. This is a striking difference from the lower-excitation 22 GHz H$_2$O masers (lower state energy level of 642 K) spread over the bipolar outflow with a much larger scale of 1000 AU (Greenhill et al. 2013). The spatial structure of the integrated intensity map of the 321 GHz H$_2$O line shows an elongation along the northeast–southwest direction, which is indicative of the bipolar outflow (Wright et al. 1995; Zapata et al. 2012; Niederhofer et al. 2012; Greenhill et al. 2013), whereas the 336 GHz map is more compact than the 321 GHz map and its extent is comparable to the present resolution (Figure 2).

To evaluate their structures, we made velocity centroid maps (peak positions of velocity channel maps) of both lines by performing two-dimensional Gaussian fitting to the synthesized images. The positional uncertainty is proportional to the synthesized beam size and is inversely proportional to the signal-to-noise ratio of the images. At the peak velocity channel of the 336 GHz H$_2$O line, the signal-to-noise ratio is $\sim$30, and hence, the positional accuracy is estimated to be as high as 0.01″. Formal errors in the Gaussian fitting, 0″.005–0″.02 (1σ), are almost consistent with this expectation.

The 321 GHz map shows an inverted Z-shaped structure with sharp ridges at the northwestern and southeastern sides connected by linearly aligned features (Figure 3(a)). This appears quite similar to previous interferometer maps of vibrationally excited ($v = 1, 2$) $^{28}$SiO masers as well as ground state ($v = 0$) $^{28}$SiO and $^{30}$SiO masers at 43 GHz and 86 GHz (Menten & Reid 1995; Wright et al. 1995; Baudry et al. 1998; Goddi et al. 2009). Thus, the vibrationally excited SiO masers and the 321 GHz H$_2$O line trace the same dynamical structure excited at the base of the northeast–southwest outflows (Kim et al. 2008; Matthews et al. 2010). In fact, the 321 GHz H$_2$O line is detected in a bipolar outflow associated with another nearby massive star-forming region, Cepheus A (Patel et al. 2007). The similarities between 321 GHz H$_2$O emission and previous vibrationally excited SiO maser observations ensures that the distribution of the H$_2$O emission traced by ALMA is reliable and can be compared with higher angular resolution maps of VLBI observations.

On the other hand, the 336 GHz H$_2$O line map perfectly fits the dark lane devoid of the vibrationally excited SiO masers in an X-shaped distribution obtained with higher resolution VLBI at 43 GHz (Figures 3(b) and (c); Kim et al. 2008; Matthews et al. 2010). The distribution of the 336 GHz H$_2$O channel maps, $\sim$0″.2 $\times$ 0″.1 (84 AU $\times$ 42 AU), is comparable to the size of the 43 GHz continuum emission (Reid et al. 2007; Goddi et al. 2011). It is most likely that the 336 GHz H$_2$O line is emitting from a midplane of the disk as traced by the 43 GHz continuum emission.

The most important finding is a clear velocity gradient along the northwest–southeast direction (Figure 4(a)). The gradient is analogous to that of the vibrationally excited SiO masers (Kim et al. 2008; Matthews et al. 2010) and is perpendicular to the northeast–southwest outflow (Wright et al. 1995; Zapata et al. 2012; Niederhofer et al. 2012; Greenhill et al. 2013). The quasi-linear velocity gradient with a lack of the highest velocity components close to the central position suggests that the 336 GHz H$_2$O line is emitting from a rotating ring-like
structure or limb of the disk in an edge-on view. If we simply assume a linear velocity gradient of the rotating edge-on ring with a radius of 42 AU, the enclosed mass is estimated to be $5 M_\odot$. Although this value is smaller than the previous estimate of $(7–8) M_\odot$ (Kim et al. 2008; Matthews et al. 2010), a slightly larger radius of 47 AU yields a consistent value of $7 M_\odot$. These results are much lower than another estimate, $20 M_\odot$, according to the conservation of momentum of Source I and the BN object estimated from their proper motions (Gómez et al. 2008; Goddi et al. 2011). Because the mass derived from the velocity gradient, $(5–7) M_\odot$, is regarded as a rotationally supported part of the system, it could be a lower limit of the total mass of Source I. If this is the case, it implies that non-gravitational forces such as magnetic field and/or radiation pressure would efficiently
Shown with parameters of a two-dimensional Gaussian fitting of each channel map. Models are also shown with parameters of \((r_{\text{in}} = 45 \text{ AU}, r_{\text{out}} = 50 \text{ AU}, T_{\text{ex}} = 3000 \text{ K})\) and \(M_{\text{out}} = 7 M_{\odot}, \) \((2) r_{\text{in}} = 45 \text{ AU}, r_{\text{out}} = 50 \text{ AU}, T_{\text{ex}} = 3000 \text{ K}, \) and \(M_{\text{out}} = 10 M_{\odot}\) (model (4), the same as (1) but with \(T_{\text{ex}} = 4500 \text{ K}\) and model (4), the same as (1) but with \(T_{\text{ex}} = 1500 \text{ K}\). The observed PV diagram and spectral profile can indeed be explained with a ring-like structure rather than a disk without a central hole.

Next, we verify models with different enclosed masses. When we employ a larger mass of \(M_{\text{rot}} = 10 M_{\odot}\), the velocity gradient becomes steeper and the spectral profile becomes broader, similar to the model with smaller ring size (model (2) in Figure 4). When we fit the model spectrum with \(M_{\text{rot}} = 10 M_{\odot}\) to the observed line profile, we should have assumed a larger disk size of \(r_{\text{out}} > 70 \text{ AU}\). However, widths of position offsets of such model PV diagrams became significantly larger than the observed results. Therefore, our results favor a lower value of \(\sim 7 M_{\odot}\) consistent with the previous VLBI results (Kim et al. 2008; Matthews et al. 2010).

Finally, we estimate the excitation temperature of the 336 GHz H_{2}O line, \(T_{\text{ex}}\), by fitting the observed line profile, assuming \(M_{\text{rot}} = 7 M_{\odot}, r_{\text{in}} = 45 \text{ AU}, \) and \(r_{\text{out}} = 50 \text{ AU}\), respectively. We find that the observed spectral profile can be reconciled with an excitation temperature of \(>3000 \text{ K}\) and a uniform H_{2}O density of \(5 \times 10^{5} \text{ cm}^{-3}\) (e.g., models (1) and (3) in Figure 4(b)). When we assume lower excitation temperatures, the dip of the double-peaked profile becomes shallower due to the increase in optical depth (model (4) in Figure 4(b)). Note that these values could not be constrained due to a lack of multi-transition data for an excitation analysis such as the rotation diagram method.

Although we cannot rule out a possibility of excitation of the 336 GHz H_{2}O line via maser action, it is proposed to be thermalized via collisional and/or radiative excitation in a red supergiant VY CMa (Menten et al. 2006), which is consistent with a theoretical prediction (Alcolea & Menten 1993). Under this condition, its excitation temperature directly reflects a high kinetic temperature. Furthermore, because the existence of H_{2}O suggests an absence of fully ionized gas, the temperature would be lower than \(\sim 4500 \text{ K}\) as estimated from radio and infrared observations (Reid et al. 2007; Testi et al. 2010; Plambeck et al. 2013). The temperature range of 3000–4500 K is significantly higher than that expected for a radiative equilibrium with the expected luminosity of Source I, \(10^{4}–10^{5} L_{\odot} (\sim 1000 \text{ K})\). Along with the ring-like structure, this may imply a heating mechanism via accretion shock in the disk midplane (Reid et al. 2007; Testi et al. 2010; Plambeck et al. 2013).

5. DISCUSSION

In order to reconstruct the observed PV diagram and spectral profile of the 336 GHz H_{2}O line, we here employ a model of an edge-on rotating disk assuming a ring-like structure with uniform temperature/density for simplicity. Because of the limited spatial resolution (0′′4 = 168 AU), it is hard to solve a degeneracy of disk parameters, such as mass, size, and temperature, based on our present observations with a single transition at 336 GHz. Thus, what we have done is a proof-of-concept model calculation to demonstrate that the observed PV diagram and spectral profile can indeed be explained with reasonable physical and dynamical parameters consistent with previous observations.

First, we calculated models for several parameter sets of inner and outer radii of the ring, \(r_{\text{in}} = 5, 15, 25, 35, 45, 55 \text{ AU}\) and \(r_{\text{out}} = 40, 50, \) and 60 AU with a constraint of \(r_{\text{out}} > r_{\text{in}}\), for a fixed enclosed mass of \(M_{\text{rot}} = 7 M_{\odot}\) (rotationally supported mass) consistent with previously estimated lower limits (Kim et al. 2008; Matthews et al. 2010). As a result, the model with \(r_{\text{in}} = 45 \text{ AU}\) and \(r_{\text{out}} = 50 \text{ AU}\) is found to reproduce the observed PV diagram and spectral profile (i.e., model (1) in Figure 4) well. If we assume smaller inner radii, models show steep velocity gradients and higher velocity components close to the central position. Furthermore, smaller inner radii yield broader linewidths which result in a larger discrepancy between the observed and model profiles. Thus, our results favor a ring-like structure rather than a disk without a central hole.

6. SUMMARY

We detected a hot neutral circumstellar disk rotating around Source I with a scale of 100 AU in diameter. We derived the rotationally supported enclosed mass of \(7 M_{\odot}\), which could be a lower limit of the total mass of the Source I system. Because the fully ionized H ii region is not significantly evolved, Source I would be in a very early phase of a massive protostar being formed via disk accretion (Reid et al. 2007; Testi et al. 2010; Plambeck et al. 2013). Nevertheless, the estimated parameters of...
the disk, such as inner/outer radii of the ring-like structure, enclosed mass or rotationally supported mass, and excitation temperature, are still uncertain because of a lack of spatially resolved data. In fact, we still see some deviation between the model and observed results in the PV diagram and spectral profile. Further higher angular resolution observations of the multi-transition H$_2$O lines with ALMA will be crucial in order to determine more detailed physical and dynamical properties of the massive protostar Source I and its surrounding circumstellar disk.

We are grateful to T. Hosokawa, M. Momose, H. Nomura, N. Sakai, and S. Yamamoto for valuable discussions and K. Hada and A. Kataoka for useful comments. This Letter makes use of the following ALMA data: ADS/JAO.ALMA#2011.0.00199.S. ALMA is a partnership of ESO (representing its member states), NSF (USA), and NINS (Japan), together with NRC (Canada) and NSC and ASIAA (Taiwan), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO, and NAOJ. T.H. is supported by MEXT/JSPS KAKENHI grant Numbers 21224002, 24684011, and 25108005, and the ALMA Japan Research Grant of NAOJ Chile Observatory, NAOJ-ALMA-0006. M.H. is supported by MEXT/JSPS KAKENHI grant Numbers 24540242 and 25120007.

Facility: ALMA

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