

ALMA observations of submillimeter H₂O and SiO lines in Orion Source I

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Abstract. We present observational results of the submillimeter H₂O and SiO lines toward a candidate high-mass young stellar object Orion Source I using ALMA. The spatial structures of the high excitation lines at lower-state energies of >2500 K show compact structures consistent with the circumstellar disk and/or base of the northeast-southwest bipolar outflow with a 100 au scale. The highest excitation transition, the SiO ($v=4$) line at band 8, has the most compact structure. In contrast, lower-excitation transitions are more extended than 200 au tracing the outflow. Almost all the line show velocity gradients perpendicular to the outflow axis suggesting rotation motions of the circumstellar disk and outflow. While some of the detected lines show broad line profiles and spatially extended emission components indicative of thermal excitation, the strong H₂O lines at 321 GHz, 474 GHz, and 658 GHz with brightness temperatures of >1000 K show clear signatures of maser action.

Keywords. stars: individual (Orion Source I), ISM: jets and outflows, outflow, masers

1. Introduction

Orion Source I is a candidate of a high-mass young stellar object (Menten & Reid 1995) located in the nearest high-mass star-forming region Orion KL at a distance of ~ 420 pc (Menten *et al.* 2007, Kim *et al.* 2008). It drives a low-velocity bipolar outflow along the northeast-southwest (NE-SW) direction with a 1000 au-scale in edge-on view (Greenhill *et al.* 2013). Source I is known as one of the rare star-forming regions associated with the SiO masers (Menten & Reid 1995). The vibrationally excited SiO masers trace a rotating outflow arising from a circumstellar disk with a ~ 100 au scale (Kim *et al.* 2008, Matthews *et al.* 2010). The rotation curve of the SiO masers implies an enclosed mass of $(5-7)M_{\odot}$ under the assumption of Keplerian rotation, which is also confirmed by recent observations with ALMA (Plambeck & Wright 2016). However, the above mass estimate is significantly smaller than that from proper motion measurements with VLA, in which Source I is proposed to be a $20 M_{\odot}$ binary system formed by a dynamical encounter event 500 years ago (Goddi *et al.* 2011, Rodríguez *et al.* 2017, Bally *et al.* 2017). Observations of Source I at higher angular resolution would be crucial to investigate detailed physical and dynamical properties of Source I. For this purpose, strong maser lines will be unique probes as they can reveal high density and temperature regions in close vicinity to newly born stars at higher resolution than weaker thermal molecular lines.

Table 1. Detected lines (ordered by the lower-state energy)

Molecule	Transition	ν (MHz)	E_l (K)	Beam size (arcsec)	Reference
H ₂ O	5 _{3,3} -4 _{4,0}	474689	702	0.10''	
H ₂ O	10 _{2,9} -9 _{3,6}	321226	1846	0.17''	Hirota <i>et al.</i> (2014)
H ₂ O	$v=1$, 1 _{1,0} -1 _{0,1}	658007	2329	0.26''	Hirota <i>et al.</i> (2016)
H ₂ O	$v=1$, 4 _{2,2} -3 _{3,1}	463171	2744	0.10''	Hirota <i>et al.</i> (2017)
H ₂ O	$v=1$, 5 _{2,3} -6 _{1,6}	336228	2939	0.17''	Hirota <i>et al.</i> (2014)
H ₂ O	$v=1$, 5 _{5,0} -6 _{4,3}	232687	3451	0.18''	Hirota <i>et al.</i> (2012)
H ₂ O	$v=1$, 7 _{4,4} -6 _{5,1}	498502	3673	0.09''	
²⁹ SiO	10-9	428684	93	0.08''	
SiO	11-10	477505	115	0.10''	
Si ¹⁸ O	12-11	484056	128	0.09''	Hirota <i>et al.</i> (2017)
³⁰ SiO	$v=1$, 11-10	462757	1859	0.10''	
SiO	$v=1$, 11-10	474185	1883	0.10''	
²⁹ SiO	$v=2$, 11-10	465014	3611	0.10''	
SiO	$v=2$, 10-9	428087	3614	0.08''	
SiO	$v=4$, 11-10	464245	7085	0.10''	

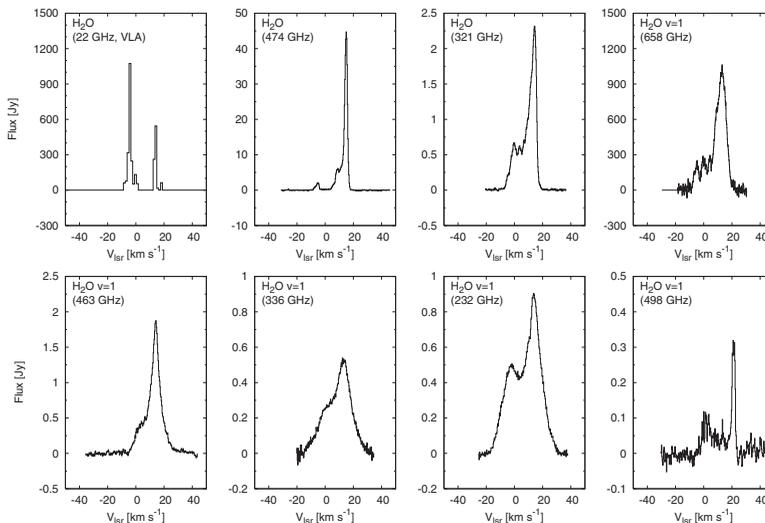


Figure 1. Spectra of the H₂O lines. For the 22 GHz (Gaume *et al.* 1998) and 658 GHz lines, total flux densities are integrated over the primary beam. Flux densities for other lines are integrated over the synthesized beam size (Table 1) around peak positions of each line.

2. Observations

Observations of the submillimeter H₂O and SiO lines were carried out with ALMA in cycles 0, 1, and 2. We also compared the ALMA Science Verification data for Orion KL at band 6. Table 1 summarizes the detected transitions. Details of observations and data analysis are described in previous papers (Hirota *et al.* 2012, 2014, 2016, 2017).

3. Results

Figures 1 and 2 show detected spectra of the H₂O and SiO lines, respectively. Intensive studies with single-dish telescopes have already detected several submillimeter H₂O lines in star-forming regions and late-type stars (Humphreys 2007) while the 463 GHz and 498 GHz lines are detected for the first time with our ALMA observations. All the spectra show broad line profiles and some of them have double peaked structures with the velocity width of ~ 10 -20 km s⁻¹. These results are analogous to previously observed

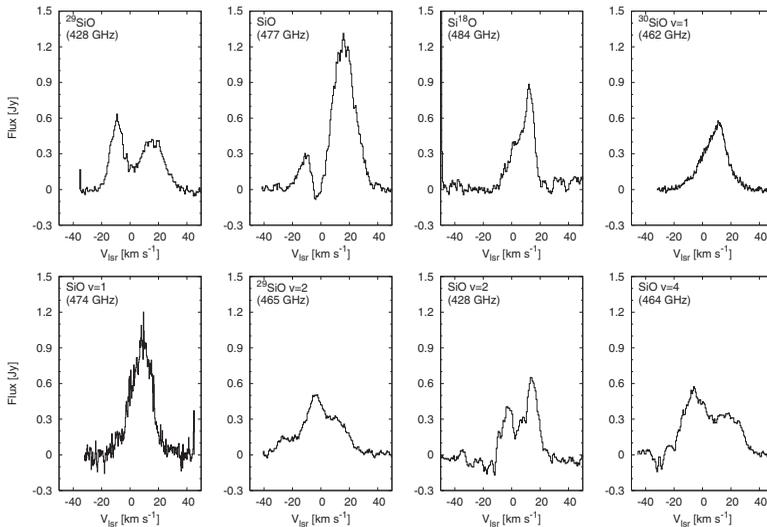


Figure 2. Spectra of the SiO lines observed toward the peak positions of each line. Flux densities are integrated over the beam size (Table 1). Note that the flux scales in all panels are common.

22 GHz H₂O masers (Figure 1; Gaume *et al.* 1998, Greenhill *et al.* 2013) and 43 GHz SiO masers (Menten & Reid 1995, Kim *et al.* 2008, Matthews *et al.* 2010).

Recent ALMA observations have revealed that high excitation molecular lines trace a hot molecular gas disk and/or base of the NE-SW outflow in Source I (Hirota *et al.* 2012, 2014, 2016, 2017, Plambeck & Wright 2016). Figure 3 shows examples of our new results from the ALMA observations. We have found a clear trend that the higher excitation lines of H₂O and SiO at the lower state energy levels of $E_l > 2500$ K could trace the compact disk or innermost region of the outflow with a 100 au scale, as can be seen in the vibrationally excited SiO masers at 43 GHz (Kim *et al.* 2008, Matthews *et al.* 2010). The highest excitation transition we have detected is the $v=4$, $J=11-10$ transition of SiO ($E_l=7085$ K), which shows the most compact structure among the detected lines (Figure 3b). On the other hand, the lower excitation lines of $E_l < 2500$ K trace the NE-SW outflow. The extended outflow structures can be traced even by the vibrationally excited $v=1$ transition of SiO (Figure 3a) with a size of >200 au. All the maps show velocity gradients perpendicular to the outflow axis, except SiO line at 477 GHz and H₂O line at 474 GHz, which are optically thick and are preferentially excited in the outer part of the outflow, respectively. These velocity structures, indicating rotation motion of the disk and outflow, provide clear evidence of magneto-centrifugal disk winds as a possible launching mechanism of the bipolar outflow from Source I (Matthews *et al.* 2010, Greenhill *et al.* 2013, Hirota *et al.* 2017).

4. Discussions

It is known that Source I is associated with the strong H₂O maser at 22 GHz and SiO masers at 43 GHz (Menten & Reid 1995, Gaume *et al.* 1998, Kim *et al.* 2008, Matthews *et al.* 2010, Greenhill *et al.* 2013). These maser emissions usually show spatially compact structures, higher brightness temperatures compared with gas kinetic temperatures, and narrow spike-like line profiles. Extremely high brightness temperatures of >1000 K of the 321 GHz, 474 GHz, and 658 GHz H₂O lines are clear signatures of maser emissions. It is also likely that a narrow spike-like spectral profile of the 498 GHz H₂O line (Figure 1) could be an evidence of maser action. However, the other lines, in particular for SiO, show

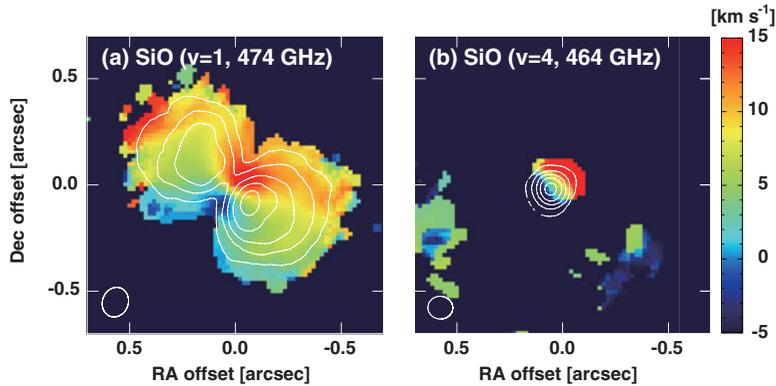


Figure 3. Moment 0 (contour) maps of (a) SiO ($v=1$, 474 GHz) and (b) SiO ($v=4$, 464 GHz) lines superposed on their moment 1 maps. Contours represent 10, 30, 50, 70, and 90% of the peak intensities of (a) $31 \text{ Jy beam}^{-1} \text{ km s}^{-1}$ and (b) $22 \text{ Jy beam}^{-1} \text{ km s}^{-1}$, respectively.

no clear signature of the above typical characteristics of masers. Flux density ratios of SiO isotopologues are different from those of isotope ratios (Tercero *et al.* 2011) suggesting maser amplification and/or self-absorption in foreground gas. In order to access excitation mechanism of the observed lines, whether they are masers or thermal emissions, further maser pumping and radiative transfer models would be essential.

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