THE FIRST DETECTION OF THE 232 GHz VIBRATIONALLY EXCITED 
H₂O MASER IN ORION KL WITH ALMA

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Abstract

We investigated the ALMA science verification data of Orion KL and found a spectral signature of the vibrationally excited H₂O maser line at 232.68670 GHz (ν₂ = 1, 5₅₋₆₄). This line has been detected previously in circumstellar envelopes of late-type stars but not in young stellar objects such as Orion KL. Thus, this is the first detection of the 232 GHz vibrationally excited H₂O maser in star-forming regions. The distribution of the 232 GHz maser is concentrated at the position of the radio Source I, which is remarkably different from other molecular lines. The spectrum shows a double-peak structure at the peak velocities of −2.1 and 13.3 km s⁻¹. It appears to be consistent with the 22 GHz H₂O masers and 43 GHz SiO masers observed around Source I. Thus, the 232 GHz H₂O maser around Source I would be excited by the internal heating by an embedded protostar, being associated with either the root of the outflows/jets or the circumstellar disk around Source I, as traced by the 22 GHz H₂O masers or 43 GHz SiO masers, respectively.

Key words: ISM: individual objects (Orion KL) – ISM: molecules – masers – radio lines: ISM

1. INTRODUCTION

Water is one of the most abundant interstellar molecules after H₂ and hence, it is important for the interstellar chemistry and physics of molecular clouds (e.g., van Dishoeck et al. 2011). However, due to large atmospheric opacity, ground-based observations of H₂O lines in the radio and infrared bands are almost impossible except for those concerning the isotopic species (e.g., HDO and H₁₈O) and strong maser lines. In particular, the 6₃₋₅₃ transition at 22 GHz (lower state energy, E₁ = 642 K) is known to show extremely strong maser emission in circumstellar envelopes (CSEs) around late-type stars, young stellar objects (YSOs) in star-forming regions (SFRs), and active galactic nuclei. The 22 GHz maser has been used as a unique probe of dense gas and their dynamics with very long baseline interferometers (VLBI) thanks to its extremely high brightness and compact structure (e.g., Chapman & Baan 2007).

Other H₂O maser lines are also detected in millimeter/submillimeter wavelength (Humphreys 2007). Lower excitation lines in 183 GHz (E₁ = 196 K) and 325 GHz (E₁ = 454 K) are detected both in CSEs and around YSOs while some of the higher excitation lines including vibrationally excited lines are detected only in CSEs. Multi-transition studies of H₂O maser lines could be powerful tools to investigate shocked regions in CSEs and YSOs at the highest spatial resolution achieved with VLBI and millimeter/submillimeter interferometers when combined with the theoretical models (Neufeld & Melnick 1990, 1991).

In this Letter, we report the detection of the vibrationally excited H₂O maser line at 232.68670 GHz (E₁ = 3451 K) in a massive SFR Orion KL at a distance of 420 pc (Hirota et al. 2007; Kim et al. 2008) with ALMA. This line has been detected previously in late-type stars but not in YSOs such as Orion KL (Menten & Melnick 1989). Thus, this is the first detection of the 232 GHz H₂O maser line in YSOs.

2. OBSERVATION

We employed the public data obtained with the ALMA science verification (SV) on 2012 January 20. They are part of a spectral line survey toward the Orion KL region at band 6 (215–245 GHz). The tracking center position of Orion KL was set to be R.A. = 05°35′14″35 and decl. = −05°22′35″0 (J2000). The data consist of several spectral settings and the net on-source time for each setting was about 20 minutes. The baseline lengths ranged from 17 to 265 kλ (from 22 to 345 m) and consisted of 16 × 12 m antennas. The primary beam size of each 12 m antenna is about 30′′ at band 6.

The spectral resolution of the ALMA correlator was 488 kHz, corresponding to the velocity resolution of 0.60–0.65 km s⁻¹ at the observed frequency range. Dual polarization data were observed simultaneously. We made synthesis imaging with the calibrated data for selected observing frequency ranges by using the Common Astronomy Software Applications (CASA) package. The natural-weighted beam size was 1.7 × 1.4 with the position angle of 171°. The resultant typical rms (root-mean-square) noise level is 0.01–0.03 Jy beam⁻¹ for each channel map. For comparison, we also made synthesized images of selected lines of methyl formate (HCOOCH₃) as discussed later. The mapped lines are summarized in Table 1.

In addition to the SV data, we analyzed ALMA cycle 0 data for the continuum emission at band 6 in the Orion KL region. The observation was done in the extended configuration on 2012 April 08 with 17 × 12 m antennas. The observed frequency ranges were 240–244 GHz and 256–260 GHz. The ALMA correlator was set for low-resolution wideband continuum observations and the spectral resolution was 15.625 MHz. The line emissions were subtracted from the visibility data and effective bandwidth was almost half of the observed frequency range. The synthesis imaging was done with the CASA software package. The uniform-weighted synthesized beam size was 0.74 × 0.56 at a position angle of 101°. The on-source integration time was 30 s and the resultant rms noise level.
of the continuum image was 7 mJy beam\(^{-1}\). Further details will be published in a forthcoming paper (T. Hirota et al., in preparation).

### 3. RESULTS

First, we inspected the observed spectra of the ALMA SV data around the frequency range close to the 232 GHz H\(_2\)O line. As a result, we found a significant spectral feature corresponding to a line-of-sight velocity with respect to the local standard of rest (LSR) of about 11 km s\(^{-1}\). We checked the database of molecular lines, Splatalogue,\(^3\) which is a compilation of the JPL, CDMS, and Lovas/NIST catalogs (Pickett et al. 1998; Müller et al. 2005; Lovas 2004), to confirm possible contamination of other spectral lines. We found that the torsionally excited HCOOCH\(_3\) line at 232.68393 GHz (\(v_1 = 1, 19_{10,10} - 18_{10,9}\) E) could be another candidate of this line if the source LSR velocity is about 8 km s\(^{-1}\). Thus, one should be cautious in identifying the detected lines.

It is well known that Orion KL show an enormous amount of molecular lines described as a line forest (Beuther et al. 1996). The Compact Ridge, the Northwest peak, and IRc 7. They are consistent with previous HCOOCH\(_3\) observations (Favre et al. 2011). One of the brightest peaks is coincident with the Compact Ridge, the Northwest peak, and IRc 7. They are consistent with previous HCOOCH\(_3\) observations (Favre et al. 2011). Of the brightest peaks is coincident with the Compact Ridge with integrated intensities of 3.5 Jy beam\(^{-1}\) km s\(^{-1}\) and 4.9 Jy beam\(^{-1}\) km s\(^{-1}\) for the blended HCOOCH\(_3\)/H\(_2\)O feature and the pure HCOOCH\(_3\) line, respectively. However, one can note a striking difference in that only the blended HCOOCH\(_3\)/H\(_2\)O feature shows a significant peak at the position of Source 2. This source is also associated with the strong SiO masers (Reid et al. 2007; Kim et al. 2008) and 22 GHz H\(_2\)O masers (Gaume et al. 1998). By subtracting the pure HCOOCH\(_3\) map from the blended HCOOCH\(_3\)/H\(_2\)O map, the residual emission component is clearly concentrated at the Source 1 position as shown in Figure 1(c). This is thought to be the contribution from the H\(_2\)O line. A negative component in the Compact Ridge could be due to an intensity variation of the HCOOCH\(_3\) maps between the two transitions. We also imaged five more HCOOCH\(_3\) lines that are not affected by contamination from other molecular lines (Table 1), and we found that none of them shows a significant peak at the Source 1 position. Therefore, emission features in the blended HCOOCH\(_3\)/H\(_2\)O map can be distinguished between HCOOCH\(_3\) and H\(_2\)O lines; HCOOCH\(_3\) is extended over the Hot Core, the Compact Ridge, the Northwest peak, and IRc 7 while H\(_2\)O is only distributed around Source 1.

Then we made synthesis images of the spectral feature of the 232.68393 GHz HCOOCH\(_3\) line and/or the 232.68760 GHz H\(_2\)O line (hereafter the blended HCOOCH\(_3\)/H\(_2\)O feature) by using the calibrated SV data. The results are shown in Figure 1. For comparison, we show a reference image of another HCOOCH\(_3\) line at 232.73862 GHz (\(v_1 = 1, 19_{8,11} - 18_{10,10}\) E) having a similar frequency, lower state energy, and expected intensity (hereafter we call this line pure HCOOCH\(_3\) feature). As can be seen in Figure 1, overall distributions and peak intensities are quite similar. For example, both the blended HCOOCH\(_3\)/H\(_2\)O and the pure HCOOCH\(_3\) maps show four dominant compact condensations coincident with the Hot Core, the Compact Ridge, the Northwest peak, and IRc 7. They are consistent with previous HCOOCH\(_3\) observations (Favre et al. 2011).

### Table 1

| Molecule       | Transition      | \(\nu\) (GHz) | \(E_l\) (K) | Note                  |
|----------------|-----------------|---------------|------------|-----------------------|
| H\(_2\)O (\(v_2 = 1\)) | 5_1,0–6_4,3     | 232.68670     | 3451       | Blended feature       |
| HCOOCH\(_3\) (\(v_1 = 1\)) | 19_{10,10}–18_{10,9} E | 232.68939     | 354        | Blended feature       |
| HCOOCH\(_3\) (\(v_1 = 1\)) | 19_{8,11}–18_{10,10} E | 232.73862     | 331        | Pure HCOOCH\(_3\)     |
| HCOOCH\(_3\) (\(v_1 = 1\)) | 18_{14,14}–17_{14,13} A | 230.87881     | 290        | Not shown in this Letter |
| HCOOCH\(_3\) (\(v_1 = 1\)) | 18_{14,14}–17_{14,13} E | 231.72416     | 290        | Not shown in this Letter |
| HCOOCH\(_3\) (\(v_1 = 1\)) | 19_{10,9}–18_{10,8} E | 231.74976     | 355        | Not shown in this Letter |
| HCOOCH\(_3\) (\(v_1 = 1\)) | 19_{11,9}–18_{11,8} E | 232.37770     | 368        | Not shown in this Letter |
| HCOOCH\(_3\) (\(v_1 = 1\)) | 19_{16,16}–18_{16,15} E | 235.73208     | 312        | Not shown in this Letter |

\(^3\)http://www.splatalogue.net/
as the methyl acetylene \( ^{13}\text{CH}_3\text{CCH} \) and acetone \((\text{CH}_3)_2\text{CO})\) lines at 232.67074 GHz and 232.69487 GHz, respectively. However, the channel maps show notable condensation around Source I with a velocity range wider than that of the HCOOCH\(_3\) and other molecular lines. These velocity structures can be seen more clearly in the spectra in Figure 3. The HCOOCH\(_3\) lines toward the Hot Core and the Compact Ridge show narrower line widths of about 2 km s\(^{-1}\) at the peak velocities of 8 km s\(^{-1}\). In contrast, the spectrum of the \textit{blended} HCOOCH\(_3\)/H\(_2\)O feature shows a double-peaked structure with a velocity range from −10 to 20 km s\(^{-1}\). Their peak flux densities are derived by the two-component Gaussian fitting to be 0.28 ± 0.02 Jy and 0.43 ± 0.02 Jy at a velocity of −2.1 ± 0.6 km s\(^{-1}\) and 13.3 ± 0.4 km s\(^{-1}\), respectively. On the other hand, no spectral feature is detected for \textit{pure} HCOOCH\(_3\) toward Source I.

Interestingly, the spectral profile of the \textit{blended} HCOOCH\(_3\)/H\(_2\)O feature toward Source I appears to be analogous to the 22 GHz shell masers (Gaume et al. 1998) and the 43 GHz SiO \((v = 1)\) masers (Kim et al. 2008) as shown in Figure 4. One can see a common structure showing double peaks at almost the same velocities and velocity ranges. Since the higher velocity features of the SiO \((v = 1)\) maser are slightly
vibrationally excited H₂O maser. This is the first detection of a feature detected in the ALMA SV data for Orion KL as the redshifted with respect to the H₂O maser lines, the redshifted with respect to the rest frequency of the HCOOCH₃ line, 232.68393 GHz. Other lines are identified based on the Splatalogue database as indicated in each panel.

Therefore, we can safely conclude that at least the emission feature associated with Source I is the vibrationally excited H₂O maser line at 232.68670 GHz.

4. DISCUSSION

As discussed above, we can identify the 232.68670 GHz feature detected in the ALMA SV data for Orion KL as the vibrationally excited H₂O maser. This is the first detection of this maser line in YSOs. The peak flux of the blended HCOOCH₃/H₂O feature would have a closer relation with the 22 GHz H₂O masers.

It is unlikely that other molecular lines with high-velocity components contribute to this peak because no such molecular species is known except the SiO thermal (Beuther et al. 2005; Zapata et al. 2012) and maser (Reid et al. 2007; Kim et al. 2008) lines, as well as the H₂O maser lines (Gaume et al. 1998).

Therefore, we can safely conclude that at least the emission feature associated with Source I is the vibrationally excited H₂O maser line at 232.68670 GHz.

The vibrationally excited H₂O masers have been detected in only several oxygen-rich late-type stars (Menten & Melnick 1989), which could be attributed to their higher excitation levels (3451 K) than that of the 22 GHz maser (642 K). The 232 GHz H₂O maser around Source I would be excited due to the internal heating by an embedded YSO as expected from a maser-pumping mechanism for late-type stars. Source I is also known as a powering source of the SiO masers, which is quite rare for YSOs (Zapata et al. 2009). This observational evidence may imply similar characteristics for Source I and late-type stars. Further studies of the millimeter/submillimeter masers in Source I, along with other YSOs and CSEs in late-type stars, will be crucial in understanding the pumping mechanism of the H₂O maser lines, physical and dynamical states of these maser sources, and accordingly mass-loss/accretion processes occurring in the YSOs and CSEs.

The 232.68670 GHz H₂O maser emission is concentrated around Source I. However, the distribution of the 232 GHz H₂O maser features could not be resolved with ALMA SV data with a beam size of 1′′′ × 1′′′. According to the double-peaked spectra of the 22 GHz and 232 GHz H₂O maser as shown in Figure 4, the 232 GHz maser features would have a similar structure to that of the 22 GHz masers rather than the SiO masers. Higher resolution imaging will reveal their spatial structure and provide information about a possible powering source of the 232 GHz H₂O maser—whether they are really associated with the root of outflows/jets as traced by the 22 GHz H₂O masers (Gaume et al. 1998) or with circumstellar disk as traced by the 43 GHz SiO masers (Reid et al. 2007; Kim et al. 2008).

In the present study, we could not perfectly separate the contribution from the HCOOCH₃ and the 232 GHz H₂O maser lines mainly due to the insufficient spatial resolution. Therefore, it is still unclear whether the 232 GHz masers are distributed in areas other than in Source I, such as the Compact Ridge where strong H₂O maser lines are sometimes detected (Hirota et al. 2011; Gaume et al. 1998). A search for the 232.68670 GHz H₂O maser lines with higher spatial resolution would be important to distinguish their distribution by filtering out the contribution from the thermal and extended HCOOCH₃ emission.

Our results clearly demonstrate ALMA’s high possibility of detecting new millimeter/submillimeter maser lines with its high sensitivity/resolution. Further observational studies with ALMA of millimeter/submillimeter masers will reveal spatial and velocity structure of the maser sources at a resolution of...
∼10 mas or better, providing a complementary method to the VLBI studies of the SiO and 22 GHz H$_2$O masers.

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Facility: ALMA

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In Section 2, the baseline lengths we introduced, from 17 to 265 kλ (from 22 to 345 m), were incorrect. The correct sentence is as follows:

The baseline lengths ranged from 14 to 206 kλ (from 17 to 265 m) consisted of 16 × 12 m antennas. It does not affect the results and discussion in the original paper.