Cosmic Masers: Proper Motion toward the Next-Generation Large Projects
Proceedings IAU Symposium No. 380, 2024
T. Hirota, H. Imai, K. Menten, & Y. Pihlström, eds.
doi:10.1017/S1743921323003216

The water and methanol masers in the face-on accretion system around the high-mass protostar G353.273+0.641

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Abstract. We report on a direct comparison of VLBI maser data and ALMA thermal-emission data for the high-mass protostar G353.273+0.641. We detected a gravitationally-unstable disk by dust and a high-velocity jet traced by a thermal CO line by ALMA long-baselines (LB). 6.7 GHz CH_3OH masers trace infalling streamlines inside the disk. The innermost maser ring indicates another compact accretion disk of 30 au. Such a nested system could be caused by angular momentum transfer by the spiral arms. 22 GHz H_2O masers trace the jet-accelerating region, which are directly connecting the CO jet and the protostar. The recurrent maser flares imply episodic jet ejections per 1–2 yr, while typical separation of CO knots indicates a variation of outflow rate per 100 yr. Our study demonstrates that VLBI maser observations are still a powerful tool to explore detailed structures nearby high-mass protostars by combining ALMA LB.

Keywords. ISM:jets and outflows, accretion disks, stars: massive, stars: protostars

1. Introduction

Astronomical masers in high-mass star-forming regions have been known as a convenient tracer of several compact circumstellar structures that were only resolved by a Very Long Baseline Interferometer (VLBI). However, it was sometimes difficult to confirm what each maser traces because a resolution for complementary thermal emission was basically insufficient. Nowadays, the Atacama Large Millimeter/submillimeter Array (ALMA) long baseline (LB) provides extremely sensitive and high-resolution thermal data that allow us to directly compare a VLBI maser distribution and thermal emissions. This paper reports on a detailed comparison of H_2O/CH_3OH masers associated with a disk-jet system detected by ALMA LB toward a very young high-mass protostar.

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1.1. *Target: G353.273+0.641*

The target source, G353.273+0.641 (hereafter G353), is a relatively nearby (~ 1.7 kpc) high-mass protostar located in the NGC6357 region (Motogi *et al.* 2016). The current stellar mass (M_*) is $\sim 10\ M_\odot$ (Motogi *et al.* 2017). The accretion system in G353 was found to be oriented nearly face-on base on the VLBI kinematics of H_2O masers (Motogi *et al.* 2016). Motogi *et al.* (2019) have conducted the first ALMA LB observation at 150 GHz. They have resolved an infalling rotating envelope. An accretion rate $\dot{M}$ on to the stellar surface has been estimated as $\sim 3.0\times10^{-3}\ M_\odot\ \mathrm{yr}^{-1}$. This $\dot{M}$ suggested that the accretion age of G353 ($t_{\rm acc} = M_*/\dot{M}$) is only $\sim 3\times10^3$ yr. Motogi *et al.* (2019) have also found a compact Keplerian disk of 250 au in radius. The disk is very massive ($> 2\ \mathrm{M}_\odot$) with significant substructures, which indicates the gravitationally unstable nature. These facts indicate that G353 is still in the early evolutionary stage.

1.2. *Masers in G353*

The 6.7 GHz CH_3OH masers in G353 were reported by Motogi *et al.* (2016). The masers showed spiral-like distribution. Their kinematic analysis suggested that these masers trace infalling streamlines down to 15 au in radius. The 22 GHz H_2O masers were associated with a compact bipolar molecular jet almost along the line-of-sight (Motogi *et al.* 2016). The H_2O masers showed episodic maser flare activity. A typical time scale of the flare is ~ 1 yr (Motogi *et al.* 2016). These maser flares were accompanied by drastic changes of a maser distribution and recurrent acceleration of molecular gas. These facts have indicated episodic shock propagations and maser excitations via jet-launching events in such a short time.

2. New ALMA follow-up observations

We have performed higher-resolution observations at 230 GHz in the ALMA Cycle 6. We have aimed to completely resolve the unstable face-on disk by dust continuum emission. We also observed ^{12}CO (J = 2–1) emission to study a thermal counterpart of the maser jet. We have obtained a synthesized beam of 30 and 140 milli-arcsecond (mas) for the dust continuum and the CO line, respectively. The 1-σ image noise levels achieved were 90 and 500 μJy beam^{-1} for continuum and line, respectively. We adopted a circular beam of 30 mas for the continuum as in Motogi *et al.* (2019) in order to highlight any non-axisymmetric structure. This beam size was slightly smoothed compared to the original beam of 28×22 mas^2.

3. Direct comparison of thermal disk-jet system and masers

3.1. *Spiral disk and CH_3OH masers*

We have successfully resolved the compact disk in G353. The disk has two prominent spiral arms and further clumpy substructures (see Figure 1). Although such a spiral disk has recently been reported in a few high-mass protostars (*e.g.*, Johnston *et al.* 2020; Burns *et al.* 2023), the disk in G353 is the most compact, and hence, expected to be the youngest one. The CH_3OH masers are clearly connecting the outer spiral arms and the innermost compact emission. The maser kinematics indicates the infalling streamlines, as mentioned above (Motogi *et al.* 2017). We suggest that the infalling maser streams can be caused by the removal of angular momentum via the gravitational torque of the spiral arms. The innermost compact substructure is complementary to the semi-ring-like maser distribution. This structure may trace the innermost accretion shocks at the edge of a smaller nested disk.

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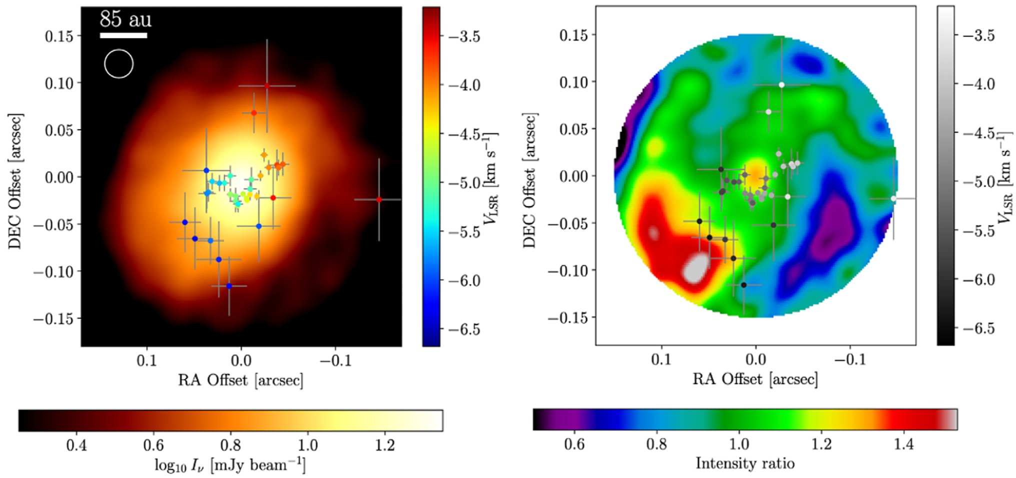

Figure 1. The left panel is the dust continuum image of the accretion disk at 230 GHz in the log scale. The color points indicates positions of 6.7 GHz CH_3OH masers reported in Motogi *et al.* (2017). The synthesized beam is presented in upper left corner. A color of each point indicate the Local Standard of Rest (LSR) velocity of each maser feature. The color in the right panel shows intensity excess map, where the original image was divided by the azimuthally-averaged value in each radius. The outside of centrifugal radius ($\sim$ 250 au) is masked. The grey points show the CH_3OH masers again.

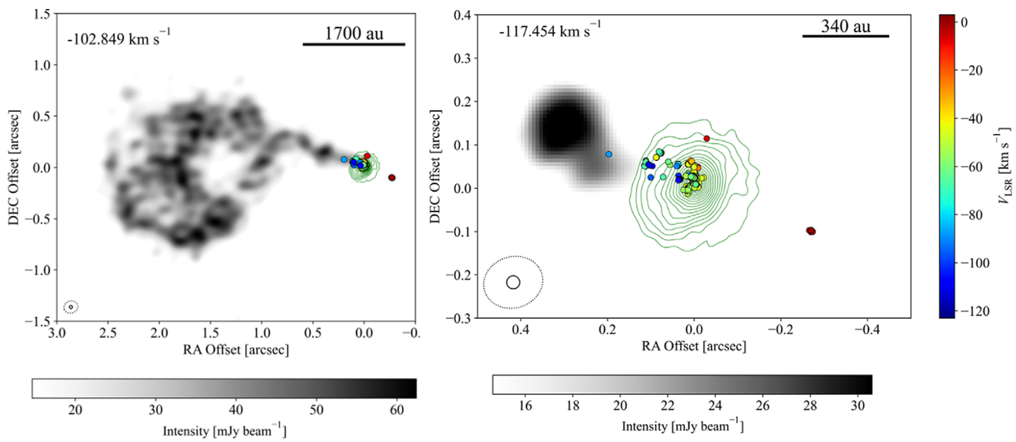

Figure 2. The grey scale in the left panel presents a channel map of the ^{12}CO jet at the LSR velocity shown in upper left corner. The right panel shows the zoom-up view of the most blue-shifted CO jet. The green contours in both panels show the dusty disk in Figure 1, which are from 10% to 99% with a step of 5% of the peak intensity. The synthesized beams for dust and CO lines are presented in lower left corners (see main text). The color points in both panels indicates the positions and LSR velocities of the H_2O masers in Motogi *et al.* (2016).

3.2. *CO jet and H_2O maser jet*

Figures 2 and 3 show channel maps of the extremely blue/red-shifted CO emission. The velocity extent of the CO jet exceeds $\pm$ 100 km s^{-1} with respect to the systemic velocity of -5 km s^{-1}. The velocity range of the blue-shifted side is up to -120 km s^{-1}. This is very similar to that of the blue-shift dominated H_2O maser emission in G353. However, the CO and H_2O masers are not spatially overlapped. The blue-shifted CO jet is distributed over an extension of the H_2O maser jet toward the East. The right panel

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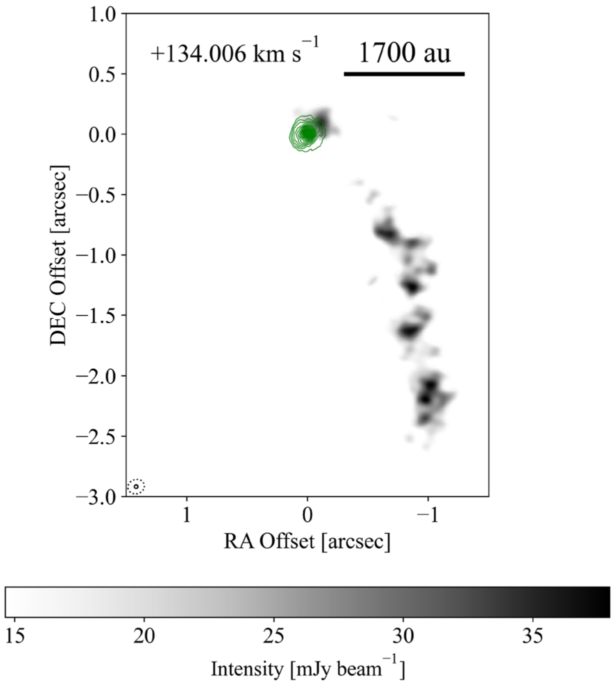

Figure 3. The grey scale shows a channel map of the red-shifted CO jet. The green contours are the same as Figure 2.

of Figure 2 shows the close-up view of the most blue-shifted CO emission. It is evident that the root of the CO jet is connected to the head of the H_2O maser jet. This geometry and the similar maximum velocity are consistent with the idea that the H_2O masers are recurrently excited in the acceleration region of the molecular jet within 100-au scale as suggested by Motogi *et al.* (2016).

Although the red-shifted CO jet is gradually bending toward the South, the overall structures are simpler compared to the blue-shifted jet, which creates a large knot at the Eastern end. A clumpy structure of the red-shifted jet suggests episodic mass ejection. A typical separation of each clump is 200–300 mas corresponding to an ejection interval of 100 yr. This ejection time is comparable to the rotation time scale of the disk at 50 au in a radius around a 10 $M_{\odot}$ protostar. But the launching point expected from the escape velocity is much smaller ($\sim$ 1 au). This fact could imply that the variation of CO jet is caused by episodic accretion (*e.g.*, Machida & Basu 2019). In this case, the infall rate could become non-steady at the scale of the CH_3OH streamlines. On the other hand, the shock propagation intervals traced by H_2O maser flares are much shorter ($\sim$ 1 yr). It may reflect some dynamical perturbations at the jet launching point ($\sim$ 1 au) or typical driving interval of a magnetohydrodynamic jet via amplification and relaxation of magnetic pressure.

Our combined ALMA-VLBI study has confirmed the association of masers with the innermost disk-jet system. Moreover, the masers reveal numerous suggestive substructures that elude even the high-resolution capabilities of the ALMA LB. We conclude by emphasizing that this combined approach significantly enhances the value of both VLBI and ALMA data for investigating high-mass star-forming regions.

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