Cosmic Masers - from OH to H_0
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Intermittent maser flare around the high-mass young stellar object G353.273+0.641

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Abstract. The water maser site associated with G353.273+0.641 is classified as a dominant blueshifted H_2O maser, which shows an extremely wide velocity range ($\pm$ 100 km s^{-1}) with almost all flux concentrated in the highly blueshifted emission. The previous study has proposed that this peculiar H_2O maser site is excited by a pole-on jet from high mass protostellar object. We report on the monitoring of 22-GHz H_2O maser emission from G353.273+0.641 with the VLBI Exploration of Radio Astrometry (VERA) and the Tomakamai 11-m radio telescope. Our VLBI imaging has shown that all maser features are distributed within a very small area of 200$\times$200 au^2, in spite of the wide velocity range ($>$ 100 km s^{-1}). The light curve obtained by weekly single-dish monitoring shows notably intermittent variation. We have detected three maser flares during three years. Frequent VLBI monitoring has revealed that these flare activities have been accompanied by a significant change of the maser alignments. We have also detected synchronized linear acceleration (-5 km s^{-1}yr^{-1}) of two isolated velocity components, suggesting a lower-limit momentum rate of 10^{-3} M$_\odot$ km s^{-1}yr^{-1} for the maser acceleration. All our results support the previously proposed pole-on jet scenario, and finally, a radio jet itself has been detected in our follow-up ATCA observation. If highly intermittent maser flares directly reflect episodic jet-launchings, G353.273+0.641 and similar dominant blueshifted water maser sources can be suitable targets for a time-resolved study of high mass protostellar jet.

Keywords. masers, stars: early-type, stars: formation, ISM: jets and outflows

1. Introduction

G353.273+0.641 (hereafter G353) is a strong 22 GHz H_2O maser site in the southern high mass star-forming region NGC6357 (Skellis *et al.* 1984). The source distance is 1.7 kpc from the sun (Neckel 1978). Multi-epoch ATCA observation has been reported in Caswell & Phillips (2008) (hereafter CP08). Class II CH_3OH maser emission ($J_k = 5_1$–6_0 A$^+$) at 6.668519 GHz is also associated with this source (CP08), and hence, the host young stellar object (YSO) is identified as a high mass YSO (e.g., Minier *et al.* 2003). CP08 has also suggested that G353 is still in the pre-ultra compact (UC) H II

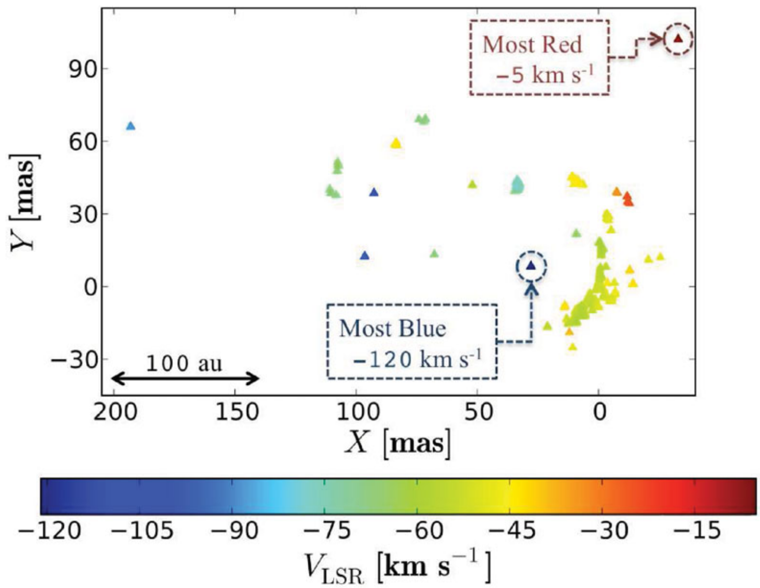

Figure 1. Spatial distribution of detected maser spots. Here, each triangle indicates detected maser spot and its color represents a line of sight velocity. The coordinate origin is $\alpha_{2000} = 17^{\rm h}26^{\rm m}01^{\rm s}.5883, \delta_{2000} = -34^\circ15'14''.905$.

region phase, i.e., high mass protostellar phase, based on the absence of any detectable OH masers (e.g., Caswell 1997; Breen *et al.* 2010).

G353 has been classified as a dominant blue-shifted H_2O maser in CP08. That is, almost all flux is concentrated in the blue-shifted emission, despite the very broad velocity range of $\pm$ 100 km s^{-1} with respect to the systemic velocity of -5 km s^{-1}. They argued that this type of masers can be caused by well-collimated jet aligned close to the line of sight. There are a few maser sources which show similar blue-shift dominance (e.g., Caswell 2004; CP08; Caswell & Breen 2010). Some of them suggest acceleration of outflowing materials in the jet. The statistical analysis in Caswell & Breen (2010) indicates that such a blue-shift dominance is a characteristic of H_2O masers at the earliest evolutionary stage of star-formation.

The exact relation between jet activity and variability of the maser is still unclear, but, once they appear, H_2O masers are an excellent tool to survey dynamic jet activities in small scale, since its bright emission allows us easy and frequent monitoring even with a small size radio telescope.

2. Long-term monitoring of the H_2O maser

Our VLBI and single dish monitoring of G353 using VERA (VLBI Exploration of Radio Astrometry) and the Hokkaido University Tomakomai 11-m radio telescope, which has been started in 2008 November and is still ongoing, has shown intermittent flare activities (see Motogi *et al.* 2011 in details). Figure 1 presents overall distribution of maser spots. We have detected only the blueshifted side of the entire maser emission reported in CP08. The most blueshifted and redshifted components are separated by only 100 mas (200 au) along the SE-NW direction.

Figure 2 shows the light-curve of the main velocity components (-53 ± 7 km s^{-1}). The observed variation is notably intermittent and there are three significant maser flares. Motogi *et al.* (2011) has revealed that these flares are accompanied by spatial varia-

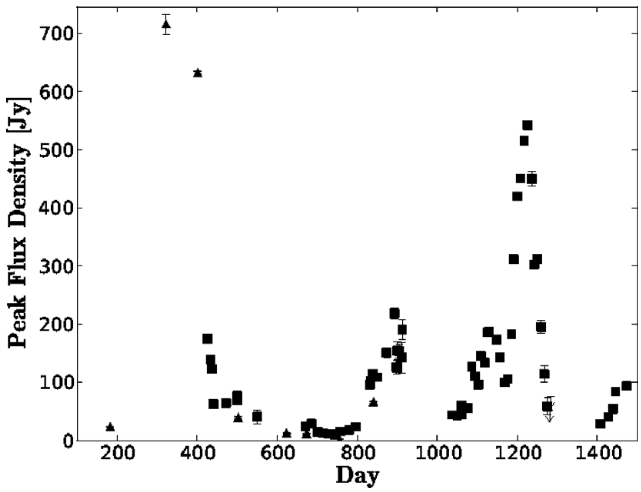

Figure 2. The light curve of the maser components at the line of sight velocity of -53 ± 7 km s^{-1}. The x-axis show relative days from the first day of 2008. The squares and triangles show single dish and VLBI data points, respectively. Follow-up single-dish data, which show the 3rd flare, are added to the dataset presented in Motogi *et al.* (2011)

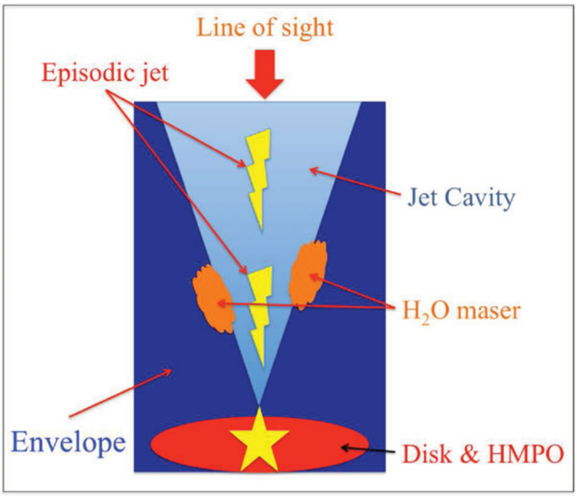

Figure 3. Schematic view of the "pole-on jet" model in G353.

tions, which can be explained by episodic shock propagation along the SE-NW direction. The characteristic velocity, which is estimated from the spatial scale of maser distribution ($\sim$100 au) divided by the time interval of three times flares ($\sim$1yr), is $\sim$500 km s^{-1}. This is rather larger than the typical three-dimensional velocity of this maser site ($\sim$100 km s^{-1}), and more like that of a radio jet seen in several HMPOs (Curiel *et al.* 2006; Martí, Rodrígues & Reipurth 1998). Motogi *et al.* (2011) has also measured the linear acceleration (5 km s^{-1} yr^{-1}) of two distinct maser clusters (see Motogi *et al.* 2011 in detail). The lower-limit momentum rate required for the acceleration is $\sim 1.1 \times 10^{-3}$ $M_{\odot}$ km s^{-1} yr^{-1}. This value is consistent with that of the outflows driven by high mass YSOs (Arce *et al.* 2007).

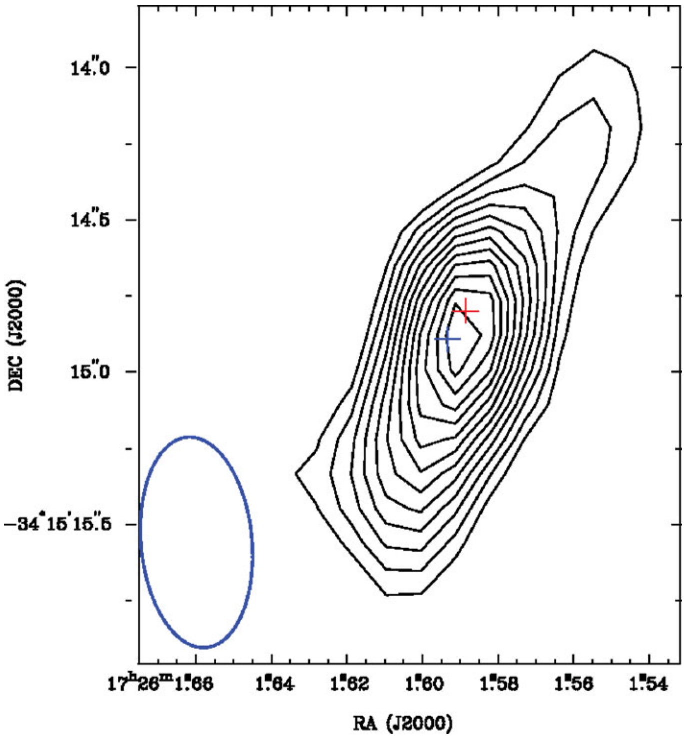

Figure 4. ATCA contour image of 22 GHz radio continuum emission from G353. Contour levels are 105 to 545 μJy beam^{-1} in steps of 40 μJy beam^{-1}. The lowest level corresponds to 3 σ noise. The synthesized beam ($0''.69 \times 0''.36$) is shown in the lower left corner. The most red and blue maser components are shown by red and blue cross, respectively. Relative positional error between masers and continuum is less than $0''.1$.

3. Follow-up jet survey

Since all maser properties can be consistently explained by the "pole-on jet" model (see figure 3), we have finally performed direct survey of a radio jet itself using the Australia Telescope Compact Array (ATCA). Our ATCA radio continuum observation was made at January 13 2012 in the 6A configuration. We observed two 2 GHz bands centered on 18 and 22 GHz simultaneously with the Compact Array Broadband Backend (CABB; Wilson *et al.* 2011). The observed hour-angle range is 10 hour and total on-source time is 6 hour because of fast switching (the cycle time of 3 min). The 1-σ noise level is 19 and 35 μJy beam^{-1} for 18 and 22 GHz, respectively.

As a result, we have successfully detected a weak and optically thick thermal radio jet (Motogi *et al.* 2012, in prep). Figure 4 shows ATCA contour image of 22 GHz continuum emission. The spectral index estimated from the total flux of 18 and 22 GHz continuum is about +1.5 (see table 1) and is consistent with that of a typical radio jet from an HMPO (e.g., Hofner *et al.* 2007). The jet is clearly elongated along the NW — SE direction, indicating that the jet has a finite inclination angle. This direction is consistent with the direction of the velocity gradient and shock propagation shown by our maser monitoring. This fact strongly suggests physical association between the maser and jet activities.

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Table 1. Properties of the detected radio jet

Frequency (GHz)	Peak Flux (mJy beam^{-1})	Total Flux (mJy)	Spectral Index
18	0.54 ± 0.02	0.76 ± 0.07	+1.5
22	0.59 ± 0.04	1.02 ± 0.11	

4. Future Works

Our studies have validated the "pole-on jet" model for the dominant blueshifted water masers, and we are now planning further follow-up studies in order to reveal exact relation between H_2O maser and jet activities. Simultaneous proper motion measurements of the masers are, especially, a direct way to examine their relation. Careful comparison between the maser light-curve and propagation of the jet is also valuable, because such a direct correlation between a maser and thermal emission in the time-domain have not yet been reported in a star-forming region. It will be a good example of what expected in extremely high-resolution studies of a high mass protostellar system in the ALMA era.

Furthermore, if highly intermittent variation in the maser-light curve actually traces episodic jet-launchings, then a G353-type H_2O maser source can be a suitable target for a time-resolved study of high mass protostellar jet. Single-dish based, dense maser monitoring can give us not only a unique statistical dataset about jet-variation, but also a chance to survey any time variation in the innermost region of an accretion disk along jet-launching activities.

5. Acknowledgements

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