

# KaVA Large Proposal for High-Mass Star-Formation Studies with Multiple Masers

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We have started a systematic observational study of the 22 GHz water masers and 44 GHz class I methanol masers in high-mass star-forming regions as a four-year KaVA large program since 2016. The primary aim of our project is to investigate dynamical evolution of high-mass young stellar objects and their circumstellar structures by observing spatial distributions and 3-dimensional velocity fields of water and methanol maser features. In 2016, we carried out imaging survey of the 25 water masers at 22 GHz and 19 class I methanol masers at 44 GHz selected from our initial source catalog. Based on these results, we have started proper motion measurements of 16 selected water maser sources at 22 GHz in 2018. In addition, we also selected 3 class I methanol maser sources to measure the proper motions for the first time with VLBI. We will present current status of our KaVA large program and future plans.

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## 1. Introduction

Formation processes of high-mass stars which have  $8M_{\odot}$  or larger are relatively less understood compared with those of low-mass Solar-type star-formation [1, 2]. Because of shorter evolutionary timescales and smaller population, number of nearby high-mass young stellar objects (HM-YSOs) were limited and hence, statistical studies with sufficiently high resolution were challenging. Recent high resolution and high sensitivity radio interferometer observations (e.g. JVLA, ALMA) allow statistical studies of deeply embedded HM-YSOs to reveal detailed structures of their disk/outflow systems at resolutions better than  $0.1''$  or an order of 100 au at 1 kpc distance [3]. These observations shed lights on number of unresolved questions regarding high-mass star-formation processes, in particular for dynamical properties of HM-YSOs such as mass accretion processes through disk onto HM-YSOs, feedback processes by outflows and/or radiation and origin of high-mass binaries and clusters.

High resolution VLBI observations of HM-YSOs are unique tools to complement interferometer observations. Water ( $\text{H}_2\text{O}$ ) masers at 22 GHz and class II<sup>1</sup> methanol ( $\text{CH}_3\text{OH}$ ) masers at 6.7 GHz have been employed as representative probes for VLBI observations since they are extremely strong and compact and hence, detectable with VLBI at  $\sim 1$  milli-arcsecond (mas) resolution [5, 6, 7]. These maser lines are excellent tracers of shocked gas associated with outflows, circumstellar disks, and expanding ultra-compact HII (UCHII) regions. Multi-epoch maser mapping with VLBI provide 3-dimensional velocity fields including radial velocities and proper motions of compact maser features. This is sometimes essential to estimate inclination angles of disk/outflow systems. Absolute astrometry at 1 mas or better accuracy can locate the dynamical center of HM-YSOs.

In order to investigate dynamical structures and their evolution of HM-YSOs and their circumstellar structures, we have initiated a systematic VLBI survey of the multiple maser lines as a large program (LP) of KaVA (KVN and VERA Array), which is a combined array of Korean VLBI Network (KVN) and Japanese VLBI Exploration of Radio Astrometry (VERA). In addition, to the 22 GHz water masers and 6.7 GHz class II methanol masers, we have added the 44 GHz class I methanol maser as a new probe for VLBI observations, which has been detected with KaVA as the first VLBI image [8]. These multiple masers are complementary with each other for investigating spatial and 3-dimensional velocity structures around HM-YSOs. By combining follow-up observations with VERA for astrometry, Japanese VLBI Network (JVN) and East-Asian VLBI Network (EAVN) for the 6.7 GHz class II methanol masers, Atacama Large Millimeter/Submillimeter Array (ALMA) for thermal molecular lines and continuum, and single-dish telescopes for large-scale structures traced by various molecular lines, we will investigate physical properties and 3-dimensional dynamical structures of disk, outflow, UCHII, and infalling envelope, and their relationship with the evolutionary phases of HM-YSOs [9].

## 2. Observations

KaVA consists of four 20 m antennas in VERA and three 21 m antennas in KVN. The baseline lengths range from 305 to 2270 km, providing the spatial resolutions of 1.2 mas and 0.6 mas at

<sup>1</sup>Methanol masers are divided into two classes, class I and class II [4].

22 GHz and 44 GHz, respectively. The KaVA LP for high-mass star-formation studies have been started since late 2016 for a four-years-long project. For statistical studies, we first selected 87 HM-YSOs in various evolutionary phases, based on the catalogues and single-dish surveys of the 22 GHz water masers, 44 GHz class I methanol masers, and 6.7 GHz class II methanol masers. Most of them are associated with multiple maser species and hence, suitable for our VLBI survey. In the first year, we selected 25 water maser sources at 22 GHz and 19 class I methanol maser sources at 44 GHz, for which VLBI data were not available in 2016, to check detectability with KaVA and variability of maser features. Two sources were observed in one track of 8-hour VLBI observations in the first year imaging survey. The recording rate was 1 Gbps with the  $16 \times 16$  MHz total bandwidths. The velocity resolution and total velocity coverage for the 22 GHz water masers were  $0.21 \text{ km s}^{-1}$  and  $216 \text{ km s}^{-1}$ , respectively. The correlation processing were done by using the Korea-Japan Joint VLBI Correlator (KJJVC) installed at KASI, Daejeon.

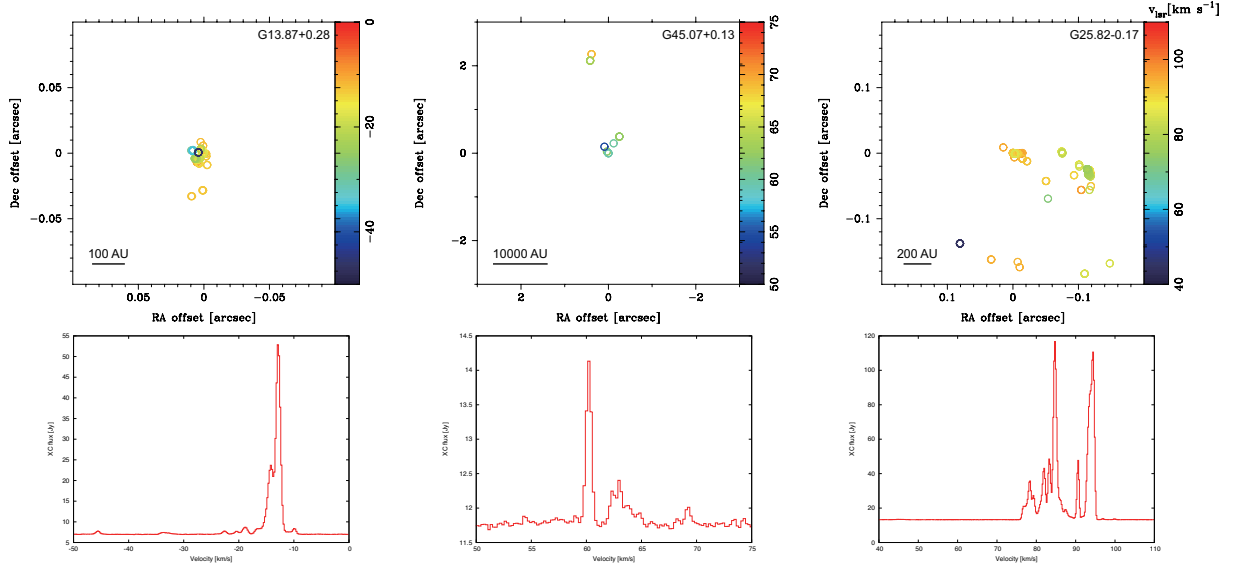
As a result of the first year observations, we selected 16 water maser sources at 22 GHz to conduct proper motion measurements in the second year. The VLBI monitoring in the second year have been started since early 2018 with 2-month interval and 4 epochs for each source ( $\sim$ half-year or longer monitoring period). Four sources are observed in one track of 8-hour VLBI session by switching target sources every 10 minutes. For some of high-velocity water maser sources, we employed spectral setting of  $8 \times 32$  MHz total bandwidths to cover velocity widths of  $430 \text{ km s}^{-1}$  but with coarser velocity resolution of  $0.42 \text{ km s}^{-1}$ . In addition, we also selected 3 class I methanol maser sources at 44 GHz to measure the proper motions for the first time with VLBI. The monitoring observations are still on-going and they will be finished by June 2019.

### 3. Results and discussion

In this section, we will mainly summarize the 22 GHz water maser observations. Figure 1 shows examples of spatial distribution maps cross-power spectra of the 22 GHz water masers associated with HM-YSO samples. The spectral profiles for some of our target sources suggest high-velocity components up to  $100 \text{ km s}^{-1}$  at maximum with respect to their systemic velocities. Thus, these high-velocity water maser sources are most likely tracing outflows driven by HM-YSOs. Except for a few examples, most of the observed HM-YSOs show multiple maser features distributed in various size scales ranging from 100 AU to 10000 AU. They also have diversity in morphology such as linearly elongated structures, compact shell-like structures, and more complex distributions, suggesting variety of outflow structures. At this moment, we have not yet estimated dynamical properties traced by the water masers because proper motion measurements have not been completed yet.

To understand basic properties of HM-YSOs associated with masers, thermal dust emission and molecular lines are essential. Follow-up ALMA observations at sub-arcsecond resolutions will be compared with our maser maps. We have obtained molecular line data of SiO and methanol at ALMA band 6 (around 210-230 GHz). These thermal lines are know to be excellent tracers of outflow and shocked gas, and hence, they can fill the gap of maser maps, which prove only spatially sparse structures. Continuum maps provide positions of HM-YSOs and their basic properties based on accurate spectral energy distribution models (SED) [10, 11]. The 3-dimensional velocity maps of maser features will be essential for constructing accurate SED models by estimating inclination

angles of disk/outflow systems of HM-YSOs. All these information will be crucial to understanding dynamical evolution of HM-YSOs and maser chronology [9].



**Figure 1:** (Top) Examples of spatial distribution maps of the 22 GHz water masers. (Bottom) Example of scalar-averaged cross-power spectra of the 22 GHz water masers.

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