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Understanding high-mass star formation through KaVA observations of water and methanol masers

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Abstract. Despite their importance in the formation and evolution of stellar clusters and galaxies, the formation of high-mass stars remains poorly understood. We recently started a systematic observational study of the 22 GHz water and 44 GHz class I methanol masers in high-mass star-forming regions as a four-year KaVA large program. Our sample consists of 87 high-mass young stellar objects (HM-YSOs) in various evolutionary phases, many of which are associated with two or more different maser species. The primary scientific goals are to measure the spatial distributions and 3-dimensional velocity fields of multiple maser species, and understand the dynamical evolution of HM-YSOs and their circumstellar structures, in conjunction with follow-up observations with JVN/EAVN (6.7 GHz class II methanol masers), VERA, and ALMA. In this paper we present details of our KaVA large program, including the first-year results and observing/data analysis plans for the second year and beyond.

Keywords. ISM: molecules — masers: ISM — stars: formation

1. Introduction

Although high-mass stars are fundamental in the formation and evolution of clusters and galaxies, their formation process of is still poorly understood (Zinnecker & Yorke 2007). This is mainly due to their fast and clustering formation and evolution in heavily obscured regions at large distances. Despite significant progress in the recent years, there are at least two competing models: turbulent core accretion vs. competitive accretion. Therefore, direct observations of the circumstellar structures (e.g., jets/outflows, accretions disks, infalling envelopes) of individual high-mass young stellar objects (HM-YSOs) are essential for understanding the formation and evolution of high-mass stars.

Various masers are associated with HM-YSOs in a wide range of evolutionary phases, and they have been utilized to probe high-mass star formation processes. Water (H_2O) masers at 22 GHz trace shocked gas regions associated with various kinds of dynamical structures including jets/outflows, disks, and HII regions. Methanol (CH_3OH) masers are divided into two classes (I & II) on the basis of their relationship with the central (proto)stars (Menten 1991). The brightest class II masers at 6.7 GHz are located close to HM-YSOs (e.g., Fujisawa *et al.* 2014), while class I masers at 44 GHz are usually located farther from HM-YSOs (e.g., Kurtz *et al.* 2004). Because of extremely high intensities, 22 GHz water masers and 6.7 GHz methanol masers have been employed as powerful tools to investigate the circumstellar spatial and velocity structures of HM-YSOs using VLBIs at resolutions of $\sim$1 milli-arcsecond (mas). In addition, we have recently reported the first VLBI imaging of 44 GHz class I methanol masers (Matsumoto *et al.* 2014), demonstrating the unique capability of the KVN and VERA array (KaVA) providing relatively short and dense *uv* coverage. These three maser species are complementary with each other for investigating overall 3-dimensional (3D) structures and dynamics around HM-YSOs by multi-epoch and multi-species VLBI studies. Such well-compiled and time-resolved VLBI datasets are quite unique in the ALMA era, allowing us to quantitatively understand the evolution of HM-YSOs and their circumstellar structures.

We started a KaVA large program in late 2015 to conduct systematic monitoring observations of 22 GHz water and 44 GHz class I methanol masers: *Understanding high-mass star formation through KaVA observations of water and methanol masers* (co-PIs: Tomoya Hirota & Kee-Tae Kim). Our program will provide the proper motion data of two maser species. We have been also conducting similar monitoring observations of 6.7 GHz class II methanol masers with the Japanese VLBI Network (JVN)/East Asian VLBI Network (EAVN) (PI: Koichiro Sugiyama). Our sample consists of 87 HM-YSOs in various evolutionary stages. The sources were selected mainly from the KVN single-dish and fringe surveys of water and class I methanol masers (e.g., Kang *et al.* 2015; Kang *et al.* 2016; Kim *et al.* 2018; Kim, Kee-Tae *et al.* in prep.). Many of them are associated with two or more different maser species and/or high-velocity water maser features.

2. Immediate Objectives

The primary scientific goal of our KaVA large program is to understand the dynamical evolution of HM-YSOs and their circumstellar structures by measuring the spatial distributions and 3D velocity fields of the three maser species. These studies can be done only by the KaVA, which is capable of imaging all three representative masers. Through the KaVA program, we will address key issues in high-mass star formation. First, we will establish an evolutionary sequence of different maser species with statistical samples. Although various maser species are known to be associated with HM-YSOs, their relationship with the central (proto)stars is still controversial (see, e.g., Ellingsen at al. 2007 and Reid 2007). This is mainly due to a lack of high-resolution observations. We will investigate the 3D velocity structures of three maser species at a resolution of $\sim$1 mas to identify their possible powering sources at a scale of $\sim$1000 AU (e.g., Fujisawa *et al.* 2014), by combining ancillary follow-up observational data.

In addition, our program will provide powerful tools to reveal the driving mechanism of jets/outflows from HM-YSOs. Jets/outflows are one of the most important processes in star formation because of their significant role to extract angular momentum. Beuther & Shepherd (2005) proposed that initially well-collimated jets/outflows from HM-YSOs evolve into wide opening-angle outflows. However, Seifried *et al.* (2012) suggested an opposite scenario from their 3D MHD simulations, in which poorly-collimated outflows evolve into well-collimated ones with the development of Keplerian disks. It is thus worth establishing a scenario explaining when and how jets/outflows from HM-YSOs with different morphology are forming and evolving.

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Several previous studies suggested that high-velocity water maser sources are a good subsample of high-mass protostellar jets. Especially, dominant blue-shifted maser sources are the best candidates of very compact and young sources (Caswell & Phillips 2008). High-velocity water maser sources are usually characterized by quite short lifetimes of the individual maser features and hence, are studied only by well organized dense monitoring as in our KaVA program. Such a time-variability can be an important clue to time-dependent nature of accretion and outflow processes (Motogi *et al.* 2016). Moreover, we will be able to estimate inclination angles of disk-jet/outflow systems, which is essential for quantitative spectral energy distribution modeling, from the 3D velocity field and spatial distribution of high-velocity maser features. Thus, the results will provide key parameters for the theoretical works to understand physical properties of HM-YSO themselves.

3. Observing Strategy and Timeline

First year (finished): We have first conducted snap-shot imaging observations of selected targets (25 water and 19 methanol maser sources) for which no previous VLBI data were available, to check detectability of maser features. We found a variety of maser morphology and selected appropriate sources for further monitoring observations in the second year (see the next section).

Second year: We will start monitoring observations toward the selected targets (16 water and 3 methanol maser sources) to measure the internal proper motions of maser features. The number of observing epochs will be 5 for each source, and the total observing time will be 160 hours and 40 hours for K- and Q-bands, respectively.

Third year and beyond: We will continue monitoring observations to extend target sources not observed in the second year. Because non-detection ($\sim$50 sources) could be due to time variability, we will conduct fringe-check and single-dish monitoring in the second year to find additional good targets not observed in the first and second years. In addition, we will carry out intensive monitoring for specific highly variable sources reflecting episodic accretion events.

4. First-year Results

In the first year, we undertook snap-shot imaging observations of 25 water and 19 methanol maser sources without available previous VLBI data. Water masers were detected toward 21 (84%) sources. They show various distributions of water maser features, including elongated and arc-like ones (see Kim, Jungha *et al.* in this volume for details). Both blue- and red-shifted maser features were detected in 16 of the 21. We will investigate the physical and dynamical properties of the jets/outflows in combination with follow-up ALMA observations, e.g., 2015.1.01571.S (PI: Mi Kyoung Kim).

None of the observed methanol maser sources have been observed with any VLBI except G18.34+1.78SW, which was already imaged with the KaVA (Matsumoto *et al.* 2014). Among the 19, correlated data were available for 17 sources so far and 16 sources were succeeded in VLBI imaging. Only single spectral features were detected in most sources, while 2–4 maser features were detected in four sources: G357.967-0.163, G18.34+1.78SW, G28.37+0.07MM1, and G49.49-0.39 (see Figure 1). In that case, individual features are typically separated by 50–500 AU with each other and sometimes more than 1,000 AU at the largest scale. The peak flux density ratios of CLEAN component to auto-correlated spectra range from 2% to 30% (Figure 1).

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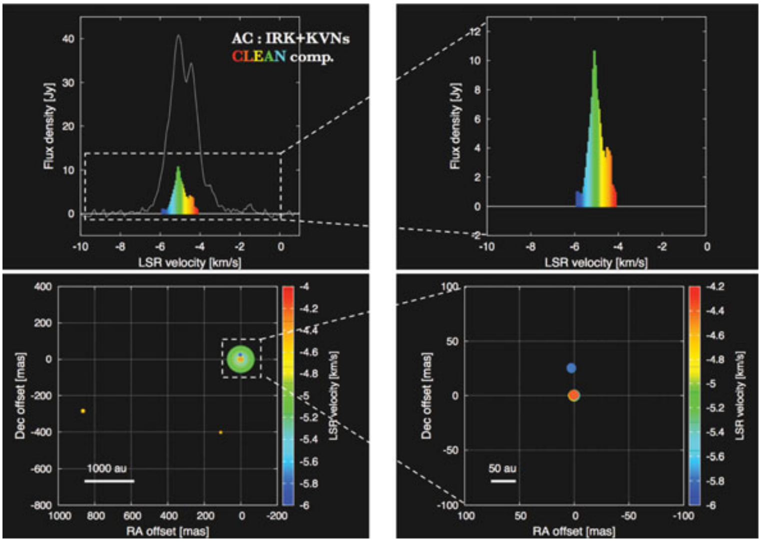

Figure 1. 44 GHz class I methanol masers in G357.967-0.163. (Upper panel) Auto-correlated spectrum (white) and sum of CLEAN components (color). (Lower panel) Spatial distribution of detected maser features.

We selected the 16 water maser sources with both blue- and red-shifted maser features and 3 methanol maser sources with three or more maser features for the second-year monitoring observations. We will be able to measure relative proper motions with respect to the brightest feature in each source, because there are sufficient number of features (>10 for the water maser and $\geqslant 3$ for the methanol maser sources).

5. Follow-up Observations

In addition to the JVN/EAVN observations of 6.7 GHz class II methanol masers, we have been performing follow-up observations using VERA and ALMA, as well. The VERA observations (PI: Tomoya Hirota) aim at determining the distances by measuring the annual parallaxes using water masers. The ALMA observations (PI: Mi Kyoung Kim) aim at investigating the physical and dynamical properties of molecular outflows associated with 44 GHz methanol masers and to identify the outflow driving sources.

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