Cosmic Masers - from OH to H_0
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KVN Single-dish Water and Methanol Maser Line Surveys of Galactic YSOs

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Abstract. We have carried out simultaneous 22 GHz H_2O and 44 GHz Class I CH_3OH maser line surveys of more than 1500 intermediate- and high-mass YSOs in the Galaxy using newly-constructed KVN 21-m telescopes. As the central (proto)stars evolve, the detection rates of the two masers rapidly decrease for intermediate-mass YSOs while the rates increase for high-mass YSOs. These results suggest that the occurrence of the two masers is closely related both to the evolutionary stage of the central objects and to the circumstellar environments. CH_3OH masers always have very similar velocities (<10 km s^{-1}) to the natal dense cores, whereas H_2O masers often have significantly different velocities. The isotropic luminosities of both masers are well correlated with the bolometric luminosities of the central (proto)stars.

Keywords. maser, water, methanol, star formation, young stellar object

1. Korean VLBI Network (KVN)

The Korean VLBI Network (KVN) consists of three 21-m radio telescopes, which are located in Seoul (Yonsei University), Ulsan (University of Ulsan), and Jeju island (Tamna University) (Kim *et al.* 2004; Kim *et al.* 2011; Lee *et al.* 2011). The three baselines are 305, 359, and 478 km. KVN is a compact VLBI network, compared to VLBA and EVN, both of which have the longest baselines $>$ 5000 km. In order to obtain more and longer baselines, KVN will be often run in combination with Japanese and Chinese VLBI facilities at 22 and 43 GHz. The so-called East Asian VLBI Network (EAVN) is expected to be comparable to VLBA or EVN in spatial resolution, sensitivity, and imaging capability (e.g., Yi & Jung 2008). In addition, KVN will be operated in four (22/43/86/129 GHz) different frequency bands simultaneously using multi-frequency band receiver systems (Han *et al.* 2008). Simultaneous multi-frequency observations will make it possible to use the 22 GHz data for performing phase calibrations of higher-frequency data (Jung *et al.* 2011). By this multi-frequency phase referencing technique, KVN could play an important role in millimeter VLBI observations of maser sources in galactic star-forming regions and evolved stars and active galactic nuclei.

Figure 1. KVN Yonsei, Ulsan, and Tamna stations.

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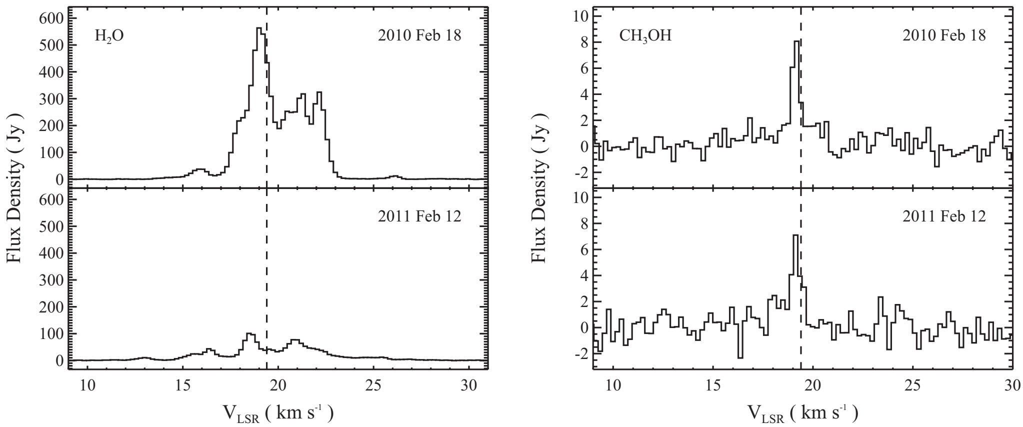

Figure 2. (a) H_2O maser spectra and (b) 44 GHz Class I CH_3OH maser spectra of UCHII G15.04−0.68. The observing date is shown at the top right corner in each panel. The vertical dotted line represents the systemic velocity of the parental dense core.

All KVN 21-m radio telescopes were equipped with 2-channel (22/43 GHz) receiving systems in 2009. We have been making single-dish observations as well as VLBI test observations. As of 2012 March, 4-channel receiving systems were installed at all KVN telescopes. We plan to start regular VLBI operation at 22/43 GHz from late 2012 and at 22/43/86/129 GHz from late 2013.

2. KVN Single-dish Maser Line Surveys of YSOs in the Galaxy

From 2009 September to 2011 June we have carried out simultaneous 22 GHz H_2O and 44 GHz Class I CH_3OH maser line surveys of more than 1500 YSOs in the Galaxy using KVN 21-m telescopes. Our sample is composed of intermediate- and high-mass young stellar objects (YSOs) in different evolutionary stages (e.g., Wood & Churchwell; Sridharan *et al.* 2002). The primary goals of these surveys are (1) to investigate the relationship between the two masers, and (2) to study the relationship of the two masers with the central (proto)stars and the natal dense cores, (3) to build a new database for higher-resolution observations of the two masers with EVLA and KVN(+VERA).

The overall detection rates of H_2O and CH_3OH masers in high-mass YSOs are about 40% and 35% with a flux limit of $\sim$0.5 Jy (1σ), respectively. The detection rates significantly increase for high-mass YSOs as the central objects evolve from the protostellar stage to the main sequence stage (see also Fontani *et al.* 2010). This is in contrast with the trend observed in low- and intermediate-mass YSOs, that the detection rates drop with the evolution of the central (pro)stars (Furuya *et al.* 2003; Bae *et al.* 2011). These results suggest that the occurrence of the two masers is closely related to the circumstellar environments as well as the evolutionary stage of the central (proto)stars. Figure 2 shows sample maser spectra detected in G15.04−0.68, which is a spherical ultra-compact HII region (UCHII) (Kim, W.-J. in preparation). CH_3OH maser lines do not usually show any significant variations in velocity, intensity, and shape over one-year period, but H_2O maser lines show significant variations. CH_3OH masers always have similar velocities to the parental dense cores within 10 $\mathrm{km\,s^{-1}}$, while H_2O masers often have many velocity components significantly shifted from the systemic velocities.

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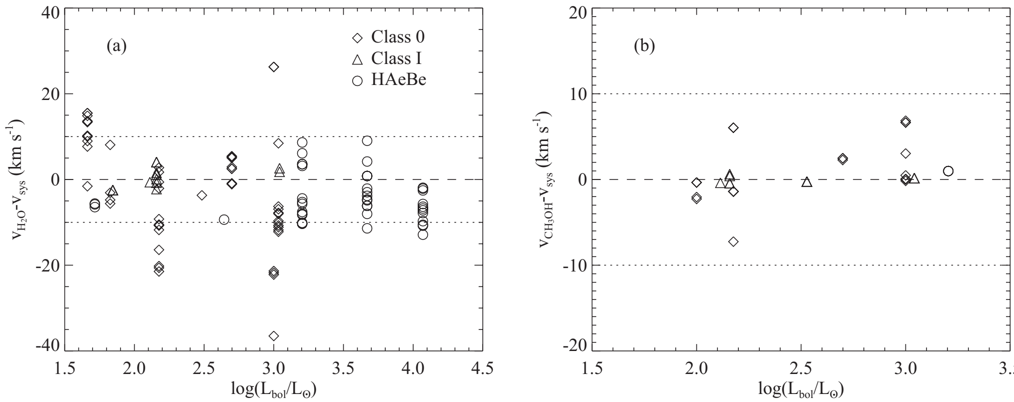

Figure 3. Relative velocity vs. bolometric luminosity of the central (proto)star for (a) H_2O masers and (b) 44 GHz Class I CH_3OH masers.

3. The Survey Results of Intermediate YSOs

In Bae *et al.* (2011) we reported a multi-epoch, simultaneous 22 GHz H_2O and 44 GHz class I CH_3OH maser line survey toward 180 intermediate-mass (4–10 $M_\odot$) YSOs. The sources consists of 14 Class 0, 19 Class I objects, and 147 Herbig Ae/Be (HAeBe) stars, which are widely believed to be intermediate-mass pre-main sequence stars.

We detected H_2O masers in 16 objects and CH_3OH masers in 10 objects with one new H_2O maser source (HH 165) and six new CH_3OH maser sources (CB 3, IRAS 00338+6312, OMC3 MMS9, IRAS 05338−0624, V1318 CygS, and IRAS 23011+6126). HH 165 is the ninth HAeBe star with detected H_2O maser emission, and V1318 CygS is the first HAeBe star with detected 44 GHz CH_3OH maser emission.The overall detection rates of H_2O and CH_3OH masers are 9 % and 6 %, respectively. The rates rapidly decrease as the central (proto)stars evolve, as for low-mass YSOs. The detection rates of H_2O masers are 50 %, 21 % and, 3 % for Class 0, Class I, and HAeBe objects, respectively. Those of CH_3OH masers for Class 0, Class I, and HAeBe objects are 36 %, 21 %, and 1 %. As mentioned above, the detection rates in high-mass star-forming regions increase as the central objects evolve.

The relative velocities of H_2O masers with respect to the ambient molecular gas are 9 $\mathrm{km\,s^{-1}}$ on average, whereas those of CH_3OH masers are tightly distributed around 0 $\mathrm{km\,s^{-1}}$. No CH_3OH maser velocity deviates more than 10 $\mathrm{km\,s^{-1}}$ from the systemic velocity. Large relative velocities are mainly shown in the Class 0 objects: $|v_{\mathrm{H_2O}} - v_{\mathrm{sys}}| >$ 10 $\mathrm{km\,s^{-1}}$ and $|v_{\mathrm{CH_3OH}} - v_{\mathrm{sys}}| > 1$ $\mathrm{km\,s^{-1}}$. This is consistent with previous suggestions that H_2O masers originate from the inner parts of outflows while class I CH_3OH masers arise from the interacting interface of outflows with the ambient dense gas (e.g., Kurtz *et al.* 2004).

The intensities and shapes of the observed H_2O maser lines were quite variable. Half of the maser-detected sources showed velocity drifts. The integrated line intensities varied by up to two orders of magnitude. On the contrary, the observed CH_3OH lines do not reveal any significant variability in intensity, shape, or velocity. The line integrals were maintained within $\sim$ 50 % over the observations. These different variability behaviors of the two masers may be connected with different emitting environments.

The isotropic luminosities of both masers are well correlated with the bolometric luminosities of the central objects (Fig. 4). The linear fits result in $L_{\mathrm{H_2O}} = 1.71 \times 10^{-9}(L_{\mathrm{bol}})^{0.97}$ and $L_{\mathrm{CH_3OH}} = 1.71 \times 10^{-10}(L_{\mathrm{bol}})^{1.22}$ when only data points of this

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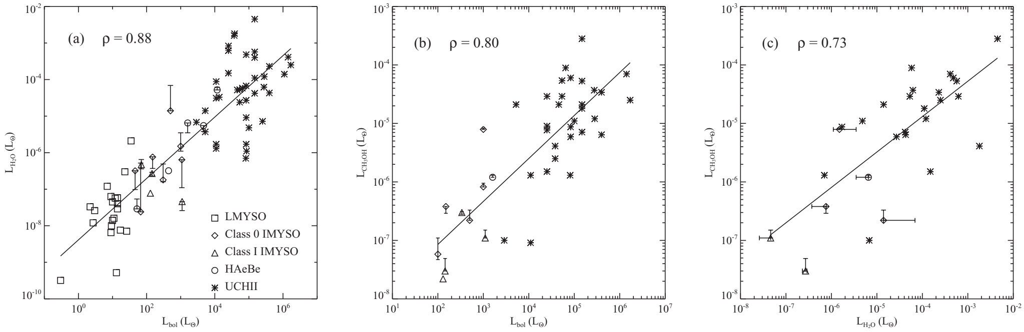

Figure 4. a) H_2O maser isotropic luminosity vs. bolometric luminosity of the central (proto)star, (b) CH_3OH maser luminosity vs. bolometric luminosity, and (c) CH_3OH maser luminosity vs. H_2O maser luminosity. In each panel, the solid line is the fitted relation to the data points and the error bars represent the variability of maser luminosity through the entire observations.

survey are considered, while those yield $L_{H_2O} = 4.10 \times 10^{-9}(L_{\rm bol})^{0.84}$ and $L_{CH_3OH} = 2.89 \times 10^{-9}(L_{\rm bol})^{0.73}$, after the data points of low- and high-mass regimes are added (Furuya *et al.* 2003; Kim, W.-J. 2012 in preparation).

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