Evolved Stars

Astrophysical Masers:
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Towards continuous viewing of circumstellar maser sources over decades

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Abstract. The brightness of maser features are fascinating and give valuable insight for circumstellar physics of oxygen-rich, intermediate-mass stars, in particular the final evolution of circumstellar envelopes (CSEs). The variety of accompanying masers such as SiO, H_2O, and OH in the CSEs may provide unique probes into different stages of rapid CSE evolution. However, with only sparse monitoring of these masers one can sometimes find it difficult to accurately interpret their spatio-kinematics, origins and excitation mechanisms. Examples can be seen in the variety of proposed models for water masers associated with "water fountains" and for silicon-monoxide masers. In order to better understand these issues, one needs to consider continuous monitoring of the individual maser gas clumps over a few stellar cycles or episodic ejection events. Here I present our previous long-term monitoring observations, especially for the water fountain source W43A. Our current efforts involve programs of intensive monitoring observations of circumstellar maser sources over decadal time periods. These programs with the East Asia VLBI Network observe H_2O and SiO maser lines simultaneously mapped at high cadence (2–8 weeks) with VLBI observations.

Keywords. masers, stars: AGB and post-AGB; mass loss, variables)

1. Introduction

Circumstellar envelopes (CSEs) are formed around evolved asymptotic giant branch (AGB) or post-AGB stars that can be isolated or in binary systems (e.g. Richards 2012). They provide opportunities to test maser pumping schemes that may be controlled by outflows in the CSEs and variable stellar radiation. However, these masers are affected by other factors such as inhomogeneity of stellar structure and mass loss (e.g. Zhao-Geisler *et al.* 2011).

The movie of SiO $v = 1$ $J = 1 \rightarrow 0$ masers around TX Cam generated from 78 observations with the VLBA†(Gonidakis *et al.* 2013) demonstrates the uniqueness and importance of long-term (for several years) and intensive (a cadence as short as 2 weeks) VLBI campaigns in order to trace the complicated spatio-kinematical and physical variations of the maser regions. Without a detailed understanding the maser excitation mechanism, it will be difficult to use masers as probes of the mechanism of stellar mass loss, affected by shock wave propagation. In addition, recurrent or episodic major mass ejections are expected in some types of AGB and post-AGB stars, such as red supergiants and stars hosting collimated fast bipolar jets (Sect. 2). The time scales of these events are longer than the stellar pulsation periods, and they may sometimes be related to the periods of binary systems. Because the central stellar systems cannot be spatially resolved except

† The VLBA is operated by the National Radio Astronomy Observatory, a facility of the National Science Foundation operated under cooperative agreement by AUI.

the nearby stars (e.g. Zhao-Geisler *et al.* 2011), circumstellar masers serve as alternative probes of such mass ejections. In these case, monitoring with high angular resolution over years or decades may be crucial for elucidating the origins and effects of ejections.

Although planning decadal long VLBI projects that observe between weekly and monthly intervals are ambitious, the present VLBI networks should encourage such projects. Indeed, the VLBA, the Japanese VLBI Exploration for Radio Astrometry (VERA)‡, and the Korean VLBI Network (KVN)¶ can do this, since are dedicated to regular and/or continuous VLBI operations (Sect. 4).

2. Exploration over decades

Decadal monitoring VLBI observations of circumstellar H_2O masers can lead to improvements or corrections of interpretations of the spatio-kinematics of the masers. One of such examples is the H_2O maser source associated with the water fountain source W43A. The model of a precessing and collimated jet, which was proposed by Imai (2007), based on the maser distributions before 2003, has been superseded by the emergence of new groups of maser features, requiring a new model of cavities of with a wide-angle jet (Fig. 1, Chong *et al.* 2016). The maser distributions found in the recent observations clarify that the maser distributions are point-symmetric and periodic (with a time spacing of 3–4 years). However, they still remain open questions, such as the origin of the intermediate velocity components located at large offsets from the jet major axis, which may be by-products of the collimated jet or a relic envelope formed at an earlier evolutionary stage (i.e. AGB phase) (Imai *et al.* 2013).

New VLBA and VERA observations of H_2O masers in IRAS 18113−2503 (at a trigonometric parallax distance of ∼12 kpc) have yielded striking maser distributions, strongly suggesting periodic generation of "bubbles" (Orosz *et al.* 2018). The evolution of existing bubbles and of newly formed inner bubbles are expected on a decade time scale, taking into account a possible period of bubble developments (∼24 years). Also ballistic motions of clumps of H_2O maser features are traceable over a decade in red supergiants (e.g. S Per, Asaki *et al.* 2018). In such sources, maser motions can exhibit large deviations from radial expansion, as suggested by numerical simulations of shocks in bipolar outflows (e.g., Ostriker *et al.* 2001; Lee *et al.* 2001). Therefore, one expects to directly detect acceleration and/or curving motions of maser with intensive VLBI monitoring observations.

3. Temporal switching of SiO maser pumping mechanisms

The pumping mechanism of circumstellar SiO masers has been a long-standing issue linked to understanding the complicated behavior of the innermost parts of CSEs. The scheme of line-overlapping with mid-infrared radiation from H_2O molecules in the warm dust (Olofsson *et al.* 1981) predicts simultaneous excitation of SiO masers at multiple vibrational levels (v =1, 2, 3, ...). This scheme has been tested in VLBI observations of the multiple maser lines ($v = 1, 2$ $J = 1 \rightarrow 0$ and $v = 1$ $J = 2 \rightarrow 1$, e.g. Soria-Ruiz *et al.* 2004), but more sensitive tracers of maser actions should be explored. Desnurs *et al.* (2014) show the distributions of SiO $v = 3$ $J = 1 \rightarrow 0$ maser emission resembling those of the $v = 1, 2$ lines.

‡ VERA/Mizusawa VLBI observatory and NRO are branches of the National Astronomical Observatory of Japan, an interuniversity research institute operated by MEXT.

¶ The KVN is a facility operated by the Korea Astronomy and Space Science Institute, supervised by the Ministry of Science, ICT and Future Planning.

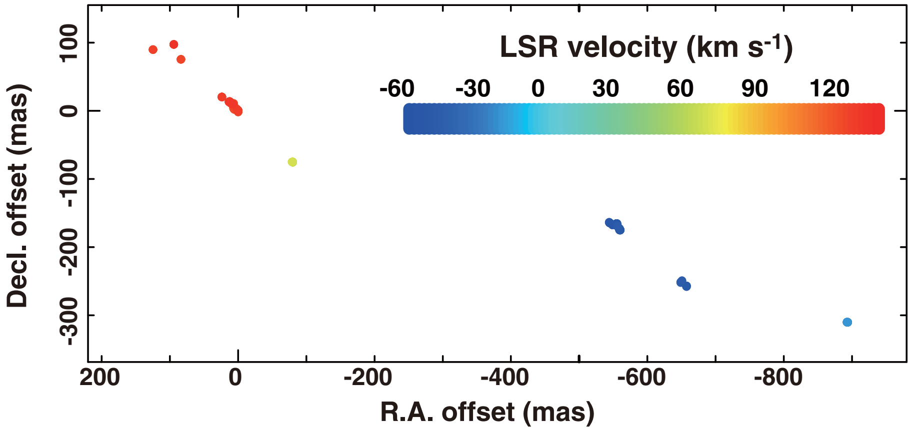

Figure 1. Distribution of H_2O masers in W43A observed on 2014 January 19 with the VLBA. New maser components were found at the south-west edge of the distribution; their locations look roughly consistent with the growth rate of the jet expected from the maser proper motions (Imai 2007). The separation between the brightest blue-shifted and red-shifted clusters of maser features has roughly persisted throughout the monitoring observations. A new intermediate-velocity component was found near the red-shifted lobe. Assuming that it is associated with an intermediate-velocity flow, the flow's expansion velocity is $\sim$30 km s^{-1}.

Interestingly, recent observations (Imai *et al.* 2010; Imai *et al.* 2012; Oyadomari *et al.* 2016) show the distributions of the $v = 3$ $J = 1 \rightarrow 0$ line significantly deviates from those of the $v = 2$ line (Fig. 2), suggesting that the line-overlapping scheme may be dependent on stellar phase. Although the significance of the spatial differences among the different maser lines should be tested in more sources, continuous tracking of the maser distributions will help to understand the origin of the temporal variations of the maser distributions.

4. Towards intensive VLBI monitoring observations

In the ALMA era, when new discoveries on circumstellar masers are coming, one area of investigation for classical (centimeter to long millimeter) masers will be to fully understand the pumping mechanisms and microscopic behaviors of these masers through conducting long-term and intensive VLBI monitoring observations as described in Sect. 1 for the sources. Towards planning such a legacy program, our ESTEMA (Expanded study on STellar MAsers) project‖ has performed a snap-shot (1–2 hours in integration time per source) imaging survey of circumstellar masers (H_2O in 22.2 GHz, SiO in 43, 86, and 129 GHz) toward 80 stars, using the combined array with the KVN and VERA (KaVA) (e.g. Yun *et al.* 2016). The hybrid observations in ESTEMA were composed of imaging with the full KaVA, dual beam astrometry with VERA, and simultaneous observations in higher frequencies (86 and 129 GHz) with the KVN. The preliminary goal is to select maser sources that are expected to be always visible and exhibit specific maser morphologies (e.g. a ring or arcs shaped by SiO masers). It has focused its main targets on long-period variable stars for further investigation about possible correlation between the maser behaviors and the light curve period and phase. In a preliminary analysis, we found maser detections as summarized in Fig. 3.

‖ https:radio.kasi.re.krkavalarge_programs.php#sh1

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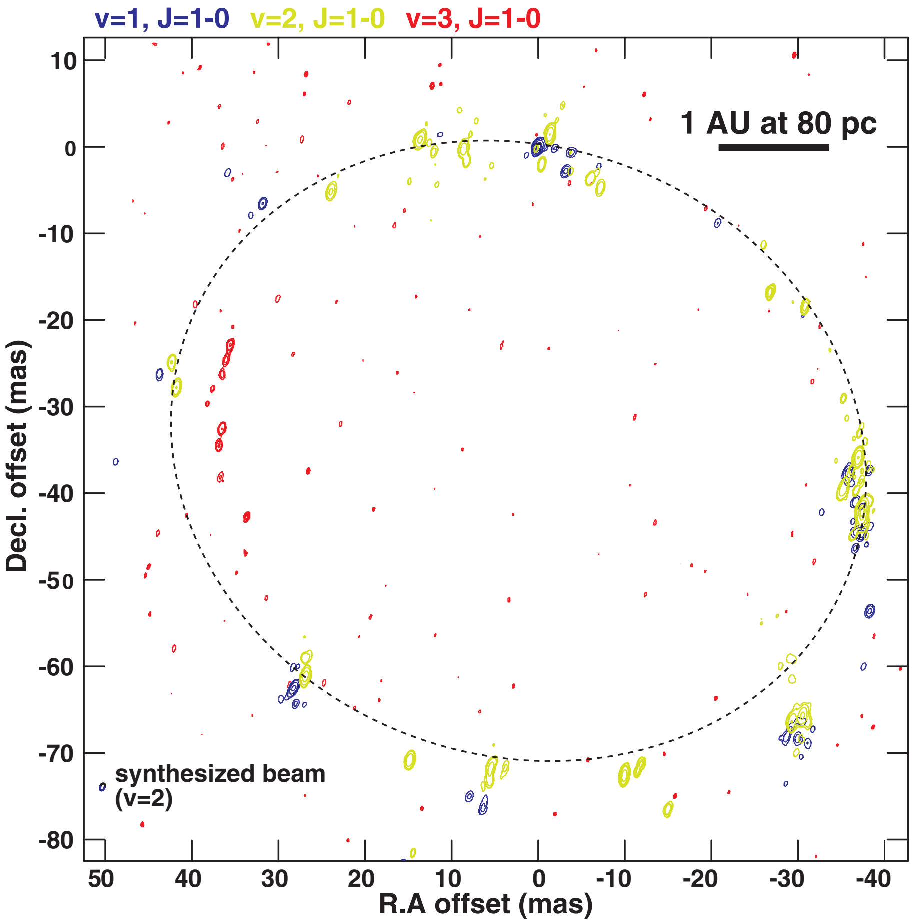

Figure 2. Distribution of SiO v =1, 2, 3 $J = 1 \rightarrow 0$ masers around W Hya observed in 2009 February with VERA (Imai *et al.* 2010). A dashed-line ellipse was fitted by eye to the distributions of the v =1 and 2 maser spots, and indicates the existence of a ring structure. Although a large fraction of the extended maser emission would be spatially resolved out, the spatial offsets of the $v = 3$ masers from the $v = 1$ and 2 masers are significant. Such large deviations were confirmed in other sources, while some sources (eg, T Cep) show excellent correlations between $v = 2$ and 3 masers using the same VLBI network (Oyadomari *et al.* 2016).

The results are roughly consistent with our expectations. Roughly half of the observed stars exhibit either H_2O and SiO maser detections, due to the variability correlated with the stellar light curves. Roughly one-third of the stars detected in either H_2O or SiO masers exhibit only one of the two molecular masers, which is attributed to the different evolutionary stages of the AGB stars hosting these masers. The 15 stars that simultaneously exhibited all of H_2O, SiO $J = 1 \rightarrow 0$ and $J = 2 \rightarrow 1$ masers will be good candidates for the VLBI monitoring observations we have planned. Adding some stars that have been already mapped, we will select the finalists in the monitoring observations from $\simeq$20 stars for the ESTEMA sample.

We note that the spatial distributions of the H_2O masers are likely to be significantly biased towards one portion of the circumstellar envelope. In fact, all the maps of H_2O masers associated with 20 stars, which were obtained from another VLBI mapping observations with the combined network with VERA, Japanese VLBI Network (JVN)

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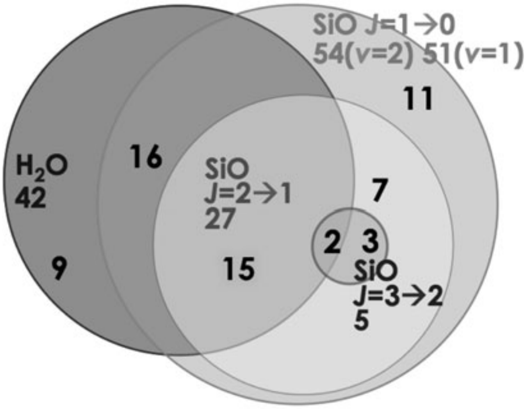

Figure 3. Venn diagram of detections of circumstellar maser lines observed in the KaVA ESTEMA project. The detections were confirmed in the cross-power spectra in scalar (or incoherent) averaging of the VLBI visibility data. The number of the $v = 2$ $J = 1 \rightarrow 0$ SiO maser detections are given in the diagram. The 15 stars hosting H_2O, SiO $J = 1 \rightarrow 0$ and $J = 2 \rightarrow 1$ masers are candidates for the intensive monitoring VLBI observations.

(yielding the shortest baseline of 55 km), and Nobeyama 45 m‡ telescopes (Imai *et al.* in preparation), exhibit such biased maser distributions although these observations were sensitive to more extended maser emission. This implies that registration of H_2O and SiO maser maps is always indispensable to precisely trace the spatio-kinematics of CSE H_2O masers with respect to the central stars surrounded by SiO maser rings.

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References

Asaki, Y., *et al.* 2018, in A. Tarchi, M. J. Reid & P. Castangia (eds.), *Astrophysical Masers: Unlocking the Mysteries of the Universe*, Proc. IAU Symposium No. 336 (Cambridge University Press: Cambridge), this volume

Cho, S.-H., Lee, C. W., & Park, Y.-S. 2007, *ApJ* 657, 482

Chong, S.-N., Imai, H., & Diamond, P. J. 2015, *ApJ* 805, 53

Desmurs, J. -F., *et al.* 2014, *A&A* 565, A127

Gonidakis, I., Diamond, P. J., & Kemball, A. J. 2013, *MNRAS* 433, 3151

Imai, H., *et al.* 2013, *ApJ* 773, 182

Imai, H., *et al.* 2012, *PASJ* 64, L6

Imai, H., *et al.* 2010, *PASJ* 62, 431

Imai, H. 2007, in: J. Chapman & W. Baan (eds.), *Astrophysical Masers and their Environments*, Proc. IAU Symposium No. 242 (Cambridge University Press: Cambridge), p. 279

Lee, C.-F. *et al.* 2001, *ApJ* 557, 429

Olofsson, H., *et al.* 1981,*AJ* 247, L81

Orosz, G., *et al.* 2018, in A. Tarchi, M. J. Reid & P. Castangia (eds.), *Astrophysical Masers: Unlocking the Mysteries of the Universe*, Proc. IAU Symposium No. 336 (Cambridge University Press: Cambridge), this volume

Ostriker, E. C., *et al.* 2001, *ApJ* 557, 443

Oyadomari, M., *et al.* 2016, in: *Proc. EVN Symposium 2016*, J. Phys. Conf. Ser. 728, 7
Richards, A. M. S.. 2012, in: Booth, R. S., Humphreys, E. M. L., Vlemmings, W. H. T. (eds.), *Cosmic Masers from OH to* H_0 , Proc. IAU Symposium No. 287 (Cambridge University Press: Cambridge), p. 199
Soria-Ruiz, R., *et al.* 2004, *A&A*, 426, 131
Yun, J. Y., *et al.* 2016, *ApJ* 822, 3
Zhao-Geisler, R., *et al.* ,2011, *A&A* 530, A120