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A study on evolved stars by simultaneous observations of H_2O and SiO masers using KVN

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Abstract. The Korean VLBI Network (KVN) is a unique millimeter VLBI system which is consisted of three 21 m telescopes with relatively short baselines. We present the preliminary results of simultaneous monitoring observations of the 22.2 GHz H_2O and 43.1/42.8/86.2/129.3 GHz SiO masers based on the KVN Key Science Project (KSP). We obtained the astrometrically registered maps of the H_2O and SiO masers toward nine evolved stars using the source frequency phase referencing method (SFPR). The SFPR maps of the H_2O and SiO masers enabled us to investigate the spatial structure and kinematics from the SiO to H_2O maser regions including the development of an outward motion from the ring-like or elliptical structures of SiO masers to the asymmetric structures of the 22.2 GHz H_2O maser features. In particular, the 86.2/129.3 GHz SiO (v=1, J=2–1 and J=3–2) masers were clearly imaged toward several objects for the first time. The SiO v=1, J=3–2 maser shows different distributions compared to those of the SiO v=1, 2, J=1–0 and v=1, J=2–1 masers implying a different physical condition.

Keywords. masers, radiative transfer, atmospheric effects, techniques: interferometric, stars: AGB and post-AGB, stars: atmospheres, stars: circumstellar matter, stars: fundamental parameters, stars: individual, stars: mass loss, supergiants

1. Introduction

Many oxygen-rich evolved stars exhibit a SiO maser emission together with a H_2O maser. The SiO masers arise from the infall and outflow regions inside the dust formation layer, while 22.2 GHz H_2O maser arises from radially accelerated regions outside the dust layer (Chen *et al.* 2007). The intensity variations of both the SiO and H_2O masers show a correlation with the optical light curve of a stellar pulsation. Therefore, it is important to perform simultaneous observations of both the SiO and H_2O masers to obtain homogeneous data-sets for both masers. However, previous maser observations were always performed separately due to the lack of those system. In addition, the VLBI observations of the 86.2 GHz SiO maser were very limited and those of the 129.3 GHz SiO maser have not been performed yet. The KVN operates at the H_2O 22 GHz and SiO 43/86/129 GHz bands simultaneously (Han *et al.* 2008) which enabled us to perform combined studies of the H_2O and SiO masers including the SiO J=2–1 and J=3–2 masers. Herein, the KVN results of evolved stars are introduced mainly based on the Key Science

Project (KSP) "Simultaneous monitoring observations of KVN 4 bands toward evolved stars" (2015, P. I. Se-Hyung Cho). The two main scientific goals of the KSP are the following. One is to investigate the spatial structure and dynamical effect from SiO to H_2O maser regions according to stellar pulsation. We also investigate the pulsation and shock wave effect from the SiO to H_2O maser region via the dust layer together by tracing the development of the asymmetric outflow motion. Another goal is to investigate the correlation and difference of the maser properties among the SiO J=1–0, J=2–1, and J=3–2 masers to provide the constraints for SiO maser pumping models.

2. Source selection and observations

At the first stage of the KSP (2015-2017), 16 target sources (`https://radio.kasi.re.kr/kvn/ksp.php`) were selected based on the KVN single dish survey (Kim *et al.* 2010, Cho & Kim 2012). Toward 16 target sources, KVN single dish monitoring was performed every two-months. Simultaneous KVN VLBI monitoring observations of H_2O 6_{16}–5_{23} (22.235080 GHz), SiO v=1, 2, J =1–0, and SiO v=1, J=2–1, 3–2 (43.122080 GHz, 42.820587 GHz, 86.243442.8 GHz and 129.363359 GHz) maser lines were performed toward the KSP sources. The VLBI observations were carried out every 1-3 months from November 2014 to May 2017. The angular resolution is 5.9 mas at 22 GHz, 3.0 mas at 43 GHz, 1.5 mas at 86 GHz, and 1.0 mas at 129 GHz (`https://radio.kasi.re.kr/kvn/status_report_2017/angular_resolution.html`). The DiFX correlator was used for the correlation with 1 s averaging and velocity resolutions of 0.2 km s^{-1} and 0.1 km s^{-1} at 22 and 43 GHz. Data reduction was performed using the NRAO AIPS software package. In addition, the SFPR method (Dodson *et al.* (2014)) and SFPR pipeline (Y. J. Yun *et al.* in preparation) were also adopted for registrations of the H_2O and SiO masers.

3. Preliminary results of several individual sources

Astrometrically registered simultaneous maps of the H_2O and SiO masers were obtained from 9 sources (VY CMa, VX Sgr, IK Tau, W Hya, WX psc, R Crt, V1111 Oph, V5102 Sgr, and V627 Cas) among the 16 KSP sources. In particular, the registered maps of the H_2O and SiO masers including the 86.2/129.3 GHz SiO (v=1, J=2–1 and J=3–2) masers were clearly imaged toward 5 sources (VY CMa, VX Sgr, IK Tau, W Hya, and WX psc) for the first time.

3.1. *Supergiant VX Sgr*

VX Sgr is a red supergiant with an optical pulsation period of 732 days (Kukarkin at al. 1970). The 4 band observational results based on five epoch data with the detection of the 129.3 GHz SiO maser (D. H. Yoon's oral presentation, in preparation) are as follows. Fig. 1 shows the astrometrically registered integrated intensity maps of the 22.2 GHz H_2O and 43.1/42.8/86.2/129.3 GHz SiO masers observed on March 27, 2016 (ϕ=0.67). The SiO maser displays a typical ring-like structure, while the H_2O maser has an asymmetric structure spread slightly in the NW and SE direction in 350 mas. The ring fitting results based on the astrometrically registered maser spot maps of SiO masers give an accurate position of the central star. The ring fitting results also show that the 42.8 GHz SiO maser is located inside the 43.1 GHz maser and the 86.2 GHz maser located at the outer region of the 43.1 GHz maser as previously reported. However, the 129.3 GHz SiO maser was located at the outermost region compared to the 43.1/42.8/86.2 GHz masers. Fig. 1 shows the variations in the ring radius of the 129.3 GHz SiO maser with respect to the

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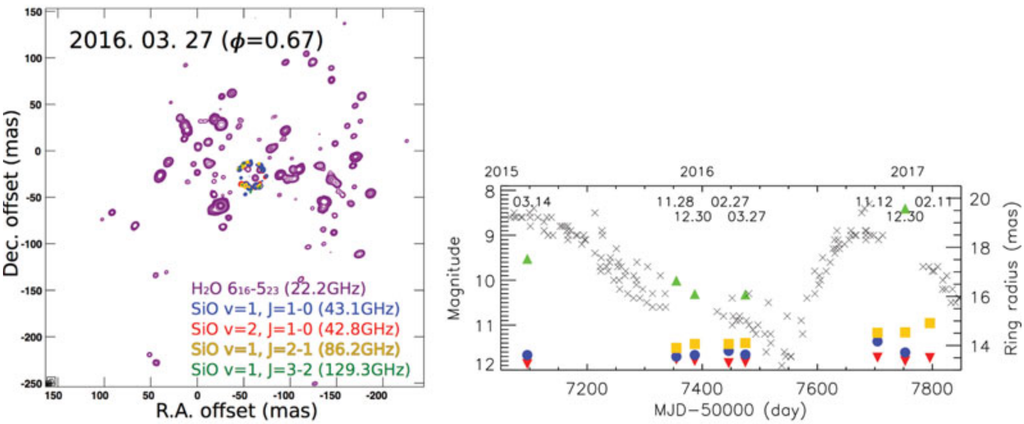

(a) (b)

Figure 1. (a) Astrometrically registered integrated intensity maps (moment zero map) of the 22.2 GHz H_2O and 43.1/42.8/86.2/129.3 GHz SiO masers toward VX Sgr obtained on March 27, 2016 (ϕ=0.67). (b) Variation of the SiO ring radius with the optical light curve. Green triangle, yellow square, blue circle, and red inverted triangle indicate the 129.3, 86.2, 43.1, and 42.8 GHz SiO masers.

optical light curve. The ring size of the 129.3 GHz maser increases around the optical maximum suggesting that radiative pumping is dominant in this maser.

3.2. *Supergiant VY CMa*

VY CMa is one of the very important objects to study the evolution of high-mass stars showing localized mass ejections (Decin *et al.* 2016). The 4 band monitoring observations were performed in 29 epochs from September 2014 to June 2017. The preliminary results based on 5 epoch data (Cho *et al.* in preparation) are presented here together with their movie. The movie for the SiO masers shows an elliptical pulsation motion in the NE-SW direction different from the ring-like pulsation motion. Fig. 2 shows representative 4 band SFPR maps of the H_2O and SiO masers observed on Dec. 1, 2016. The SiO 43/42 GHz SiO masers are active in the NE direction accompanying the isotopic ^{29}SiO v=0, J=1–0 maser. The 129.3 GHz maser arises from the inner region of the 43.1/42.8/86.2 maser features in the NE direction, while this maser arises from the outer region with extended features in the SW direction. These results may be associated with the high and low density bipolar axis oriented in the NE-SW direction (Smith *et al.* 2009, Decin *et al.* 2016). The registered maps of the SiO J=1–0, J=2–1, and J=3–2 maser lines show the different locations in the SiO maser distributions (Fig. 2). This result suggests that there are different excitation conditions and pumping mechanisms according to the different transitions. In addition, the elliptical pulsation motion in the NE-SW direction in the movie of the SiO maser seems to be related with the different pulsation mode of VY CMa compared to the fundamental mode of Mira variables.

3.3. *Mira variable IK Tau*

IK Tau is a well-studied oxygen-rich AGB star in a large number of thermal and maser lines. Mid-infrared interferometric observations show a substantially asymmetric dust shell (Weiner *et al.* 2006). We performed 4 band monitoring in 23 epochs from August 2014 to June 2017. Five epoch data (January, March, and April, 2016, and January and February, 2017) were used for the maser movie. The 43.1/42.8 GHz SiO masers were active in the SW direction while the 86.2 GHz SiO maser was active in the South. Fig. 3

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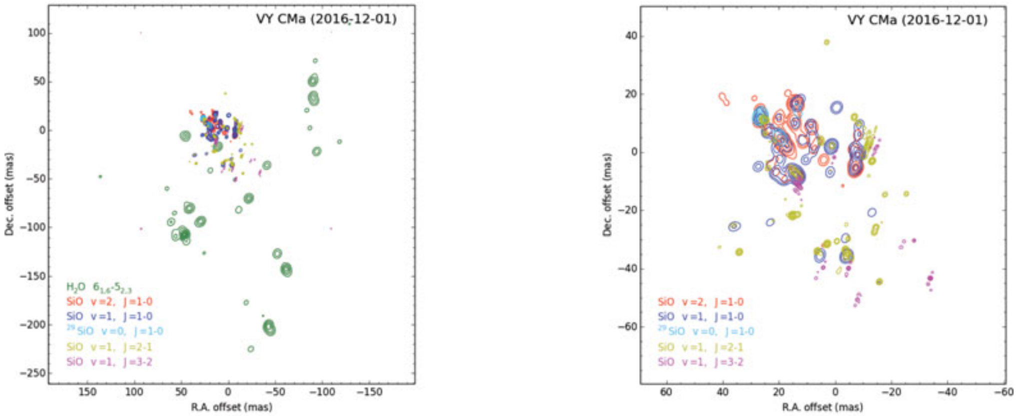
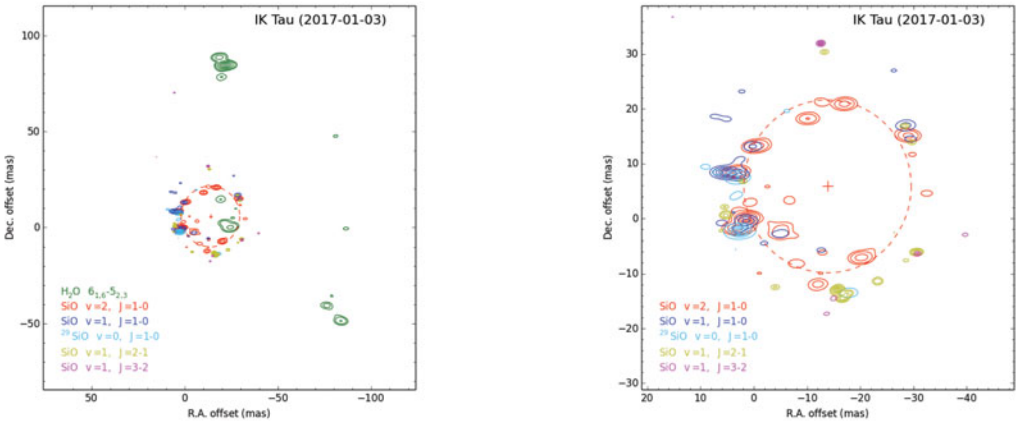


(a) All (b) SiO

Figure 2. Astrometrically registered integrated intensity maps (moment zero map) of the 22.2 GHz H_2O and 43.1/42.8/86.2/129.3 GHz SiO masers toward VY CMa obtained on December 1, 2016.



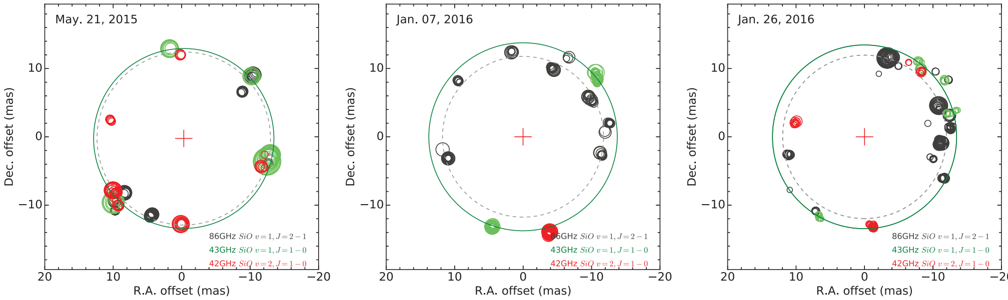
(a) All (b) SiO

Figure 3. Astrometrically registered integrated intensity maps (moment zero map) of 22.2 GHz H_2O and 43.1/42.8/86.2/129.3 GHz SiO masers toward IK Tau obtained on January 3, 2017.

shows the astrometrically registered integrated intensity maps of the 22.2 GHz H_2O and 43.1/42.8/86.2/129.3 GHz SiO masers obtained on January 3, 2017. The isotopic ^{29}SiO v=0, J=1–0 maser was located at the active region of the 43.1/42.8 GHz SiO masers. The 129.3 GHz SiO maser was located at the outer most region compared to the 43.1/42.8/86.2 GHz SiO masers. We need to compare these results of the 129.3 GHz SiO maser with those of WX Psc (Y. J. Yun *et al.* in preparation) according to the optical phases.

3.4. *Semi-regular variable R Crt*

R Crt is classified as SRb type semi-regular variable star. The SRb type variables show uncertain or superimposed periodicity which indicates a complex pulsation mode such as one or more overtones. Eleven epoch monitoring observations were performed from October 2014 to Febuary 2016. Here we present the results of three epoch data which include the successful registered maps of the 22.2 GHz H_2O and 43.1/42.8/86.2 GHz SiO



(a) Epoch 1 (b) Epoch 2 (c) Epoch 3

Figure 4. Ring fitting of the 43.1 (green) and 86.2 (grey) GHz SiO masers based on the maser spot-velocity maps.

masers (D. J. Kim *et al.* in preparation). The 129.3 GHz SiO maser was not detected due to its week intensity. The H_2O maser features are distributed in the southern part of the ring-like structure of the SiO masers showing a high asymmetric feature. We determined the dynamical center of the H_2O maser with the rind fitting center of the SiO masers. Fig. 4 shows the spot-velocity maps and ring fitting of the 43.1 and 86.2 GHz SiO masers. As shown in Fig. 4, the 86.2 GHz SiO maser spots are located more in the inner regions compared to those of the 43.1 GHz SiO maser. The previous observations (Soria-Ruiz *et al.* 2004; Soria-Ruiz *et al.* 2007) and our VX Sgr results for the 86.2 GHz SiO maser showed that the 86.2 GHz maser was distributed in the outer regions compared to those of the 43.1 GHz SiO maser. Therefore, D. J. Kim *et al.* discussed that these peculiar features of the 86 GHz SiO maser from R Crt seem to be originated from the complex dynamics caused by the overtone pulsation mode of the SRb type R Crt.

3.5. *Symbiotic star V627 Cas*

V627 Cas was included on the Belczynski *et al.* (2000) list of stars suspected to be symbiotic. The pulsation period is not regular, and the brightness varies much indicating the possible presence of flickering (Kolotilov *et al.* 1996). We obtained successful registered maps of both the H_2O and SiO masers by the SFPR method in five epochs among 14 epoch monitoring observations (H. Yang *et al.* in preparation). The registered maps including the 86.2 GHz SiO maser were obtained in three epochs. The spot distributions of the H_2O maser showed very rapid variations according to observational epochs. Therefore, we are investigating whether these variations of the H_2O maser are associated with the orbital motion of a hot companion. In addition, the spot distributions of the SiO masers did not show the ring-like structure differently from those of Mira variable stars.

4. Summary of and issues with the first stage KSP results

Based on the astrometrically registered simultaneous maps of the H_2O and SiO masers from 9 KSP sources, we are investigating the spatial structure and kinematics from the SiO to the H_2O maser regions including the development of outward motion from the ring-like or elliptical structures of the SiO masers to the asymmetric structures of the 22.2 GHz H_2O maser features. We also need to investigate the evolution of the asymmetric clumpy structure and the role of the dust layer from the SiO to the H_2O maser regions. To interpret the registered maps of the SiO and H_2O masers, both SiO and H_2O maser models coupled to the hydrodynamic atmosphere are required as well as dust shell models.

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We need collaborations with the maser theory (Gray *et al.* 2009) and VLTI (Wittkowski *et al.* 2012) teams.

The movie of the SiO masers around the supergiant VY CMa shows an elliptical pulsation motion in the NE-SW direction different from the ring-like pulsation motion in the movie of the SiO masers around the Mira variable IK Tau.

There are different features in the registered maps between the H_2O and SiO masers and also different features among the SiO maser spot distributions according to the KSP sources. We are investigating the relation with the characteristics of the sources and the evolutionary stage including the relation with the optical light curve and pulsation mode (especially, in the case of a different shape for the SiO maser features).

Based on the registered maps of the SiO J=1–0, J=2–1 and J=3–2 masers, we find that the SiO maser spot distributions are different among the SiO J=1–0, J=2–1, J=3–2 maser lines. These results imply that there are different dominant pumping mechanisms according to the different type of sources and SiO transitions.

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References

Belczynski, K., Mikolajewska, J., Munari, U. *et al.* 2000, *A&AS*, 146, 407
Chen *et al.* 2007, *ChJAA*, 7, 531
Cho, S.-H & Kim, J. 2012, *AJ*, 144, 129
Decin, L., Richards, A. M. S., Millar, T. J. *et al.* 2016, *A&A*, 592, A76
Dodson R. *et al.* 2014, *AJ*, 148, 97
Gray, M. D., Wittkowski, M., Scholz, M. *et al.* 2009, *MNRAS*, 394, 51
Han S.-T., Lee, J.-W. Kand, J. *et al.* 2008, *IJIMW*, 29, 69
Kim, J., Cho, S.-H,. Oh, C.-S., & Byun, D.-Y. 2010, *ApJS*, 188, 209
Kukarkin, B. V., Kholopov, P. N., & Efremov, Yu. N. *et al.* 1970, *General Catalogue of Variable Stars (Moscow: Acad. Sci. USSR)*
Kholopov, P. N., Samus', N. N., Kazarovets, E. V., & Kireeva, N. N. 1987, *Information Bulletin on Variable Stars*, 3058, 1
Kolotilov, E. A., Munari, U., Yudin, B. F., & Tatarnikov, A. M. 1996, *Astron. Rep.*, 40, 812
Smith, N., Hinkle, K. H., & Ryde, N. 2009, *AJ*, 137, 3558
Soria-Ruiz, R., Alcolea, J., Colomer, F. *et al.* 2004, *A&A*, 426, 131
Soria-Ruiz, R., Alcolea, J., Colomer, F. *et al.* 2007, *A&A*, 468, L1
Weiner, J., Tatebe, K., & Hale, D. D. S. *et al.* 2006, *ApJ*, 636, 1067
Wittkowski, M., Boboltz, D. A., Gray, M. D. *et al.* 2012, *Proceedings IAU Symposium*, 287, 209