Astrometrically registered maps of H$_2$O and SiO masers toward VX Sagittarii

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The supergiant VX Sagittarii is a strong emitter of both H$_2$O and SiO masers. However, previous VLBI observations have been performed separately, which makes it difficult to spatially trace the outward transfer of the material consecutively. Here we present the astrometrically registered, simultaneous maps of 22.2 GHz H$_2$O and 43.1/42.8/86.2/129.3 GHz SiO masers toward VX Sagittarii. The H$_2$O masers detected above the dust-forming layers have an asymmetric distribution. The multi-transition SiO masers are nearly circular ring, suggesting spherically symmetric wind within a few stellar radii. These results provide the clear evidence that the asymmetry in the outflow is enhanced after the smaller molecular gas clump transform into the inhomogeneous dust layers. The 129.3 GHz maser arises from the outermost region compared to that of 43.1/42.8/86.2 GHz SiO masers. The ring size of the 129.3 GHz maser is maximized around the optical maximum, suggesting that radiative pumping is dominant.

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VX Sagittarii (VX Sgr) is a red supergiant with a semi-regular variable period of 732 days\(^1\). The distance measured from SiO maser proper motion is 1.57 kpc\(^2\). The photospheric diameter is 8.82 mas\(^3\) (13.85 AU) at 2.0 \mu m. This star shows a heavy mass loss of about 2.5 \times 10^{-4} M_\odot year^{-1}\(^4\). It is well known that VX Sgr hosts strong OH, H_2O, and SiO maser emitters, compact enough for very long baseline interferometry (VLBI) observations\(^3\). The SiO masers are located at 2-4 stellar radii from the stellar surface, inside the dust-formation layer, while the 22.2 GHz H_2O maser is located outside the dust layer\(^5\), which is undergoing a radial acceleration. With the precise astrometrical registration of the SiO and H_2O masers that are observed simultaneously, we can directly compare the properties of these masers on the scales of the individual maser gas clumps for tracing the mass transfer between these layers.

The Korean VLBI Network (KVN) employing a unique quasi-optics for simultaneous observations of K (21.3–23.3), Q (42.1–44.1), W (85–95), and D (125–142 GHz) bands\(^6\) enables us to perform the combined studies of H_2O and SiO masers toward VX Sgr. This paper presents the result of the astrometrically registered, simultaneous maps of the 22.2 GHz H_2O and 43.1/42.8/86.2/129.3 GHz SiO masers using the non-integer source frequency phase-referencing (SFPR) method\(^7\). This results provide observational evidence for a break in spherical symmetry between the SiO and H_2O maser zone. The 129.3 GHz SiO maser from VX Sgr shows that radiative pumping is dominant, arising from the outermost region compared to the 43.1/42.8/86.2 GHz SiO masers.

**Results**

**H_2O and SiO maser maps and their morphological differences.** Figure 1 shows the astrometrically registered integrated intensity map of the H_2O and SiO maser lines observed on March 27, 2016 (optical phase \(\varphi = 0.67\)) toward VX Sgr\(^8\). The distributions of the SiO masers show a typical ring-like structure, while that of the H_2O maser shows an asymmetric structure spread slightly in the NW and SE direction in ~350 mas and relatively dense distributions in the NE and SW direction in ~270 mas. These results are consistent with those of multi-element radio linked interferometer network (MERLIN) and very long baseline array (VLBA) observations\(^9,10\). In addition, there are few H_2O maser features in the southern direction in contrast to those of the SiO masers.

Figure 2 shows the position–velocity spot maps according to each maser lines. The H_2O maser features show a wide-angle NE–SW biconical structure extended in slightly the NW and SE direction with respect to the position of central star (the mark “x”). The blue-shifted maser spots are dominant in the eastern part, and the red-shifted maser spots are dominant in the western part. In the case of the SiO maser, the maser components we see are mainly pumped in the tangential direction, so they show a ring-like structure in the line-of-sight. However, their partially clumped structure rather than a fully populated ring and various velocity ranges show an incoherency of the maser spot distribution. The pulsation of the stellar photosphere propagates through the SiO maser region, where dust starts to form. Al_2O_3 is likely to be the first nuclei created, at least in some lower-mass stars, and the associated SiO maser monitoring has been used to relate their appearance to the kinematics within a few R_\odot\(^11,12\). Each SiO maser line is distributed irregularly at any single epoch and, over the pulsation cycle, can show outflow and inward motion in different regions\(^13\), possibly associated with inhomogeneous dust formation. This would lead to local differences in the efficiency of radial acceleration through radiation pressure on grains and could be the cause of the irregular appearance of the 22.2 GHz H_2O masers above the dust-formation layers. Residual stellar pulsations may also affect the inner, collisionally pumped H_2O masers. The combination of our various SiO observations provides an almost perfect ring, suggesting that the average stellar wind is spherically symmetric, but the 22.2 GHz H_2O maser have an NE–SW axis of the dipole magnetic field, possibly magnetically influenced\(^15\).

**Different locations among SiO masers.** We can directly compare the maser spot distributions among the 43.1/42.8/86.2/129.3 GHz SiO masers (Table 1) in the astrometrically registered maps of Fig. 3. We can confirm the previous characteristics of the maser features and distributions according to each maser transition. In order to determine the position of the central star, we performed the ring fitting based on all spot distributions of the 43.1/42.8/86.2/129.3 GHz SiO masers. We used all of the SiO maser spots to improve the reliability and position accuracy. The mark “x” indicates the position of the central star. The ring radius obtained with the ring fitting in Fig. 2 is compared with that of the Gaussian fitting for the spot distribution histogram. Their radii obtained from both methods are consistent within the errors. Interestingly, the 86.2/129.3 GHz maser spots are located at outer regions from the central star than the 43.1/42.8 GHz maser spots (Fig. 3, Table 1). This trend has persisted at other epochs as shown in Fig. 4\(^14\). Therefore, we can confirm that the 42.8 GHz SiO maser is located inside the 43.1 GHz maser, the 86.2 GHz maser is located at the outer region of the 43.1 GHz maser, and the 129.3 GHz maser is located at the outermost region toward VX Sgr.

**Observational evidences of SiO maser pumping mechanism.** The different maser spot distributions among the 43.1/42.8/86.2/129.3 GHz SiO masers provide important information on the maser pumping mechanism. It is well known that the vibrational state \(v = 1\) (43.1 GHz) and \(v = 2\) (42.8 GHz) SiO masers at the same rotational transition \(J = 1–0\) show similar distributions with overlapping features and the \(v = 2\) SiO maser arises from the somewhat inner region of the \(v = 1\) SiO maser in many previous
VLBI observations\textsuperscript{19–21}, which is consistent with the theoretical excitation conditions of the $v = 2$ maser\textsuperscript{22}.

However, the SiO masers of the higher rotational transitions at the same vibrational state $v = 1$ (SiO $v = 1, J = 1–0, J = 2–1, J = 3–2$) shown in Fig. 3 and Table 1 arise from the outer region, i.e., the higher rotational transition masers arise further from the central star. In the case of the SiO $v = 1, J = 1–0$ (43.1 GHz) and $J = 2–1$ (86.2 GHz) masers, shock-enhanced simulation models\textsuperscript{23} accurately predict the larger radii of the 86.2 GHz SiO maser compared with those of the 43.1 GHz SiO maser as a function of the stellar pulsation phase. Their model is also supported by our observational results in which the 86.2 GHz SiO maser intensity is stronger than that of the 43.1, 42.8 GHz SiO masers in VX Sgr. The predominantly collisional pumping model predicted that the 86.2 GHz SiO maser amplification is greater than that of the 43.1 GHz SiO masers for intermediate densities\textsuperscript{24}. As another possibility, the line overlap\textsuperscript{25} can be proposed for explaining the larger ring size of 86.2 GHz maser compared to that of 43.1 GHz.

### Table 1 SiO maser ring-fitting results around VX Sgr on March 27, 2016 ($\phi = 0.67$)

| SiO transition | R.A. offset$^a$ (mas) | Dec. offset$^a$ (mas) | Ring radius$^b$ (AU) | Gaussian fit (mas) | Converted coordinate (J2000)$^c$ |
|----------------|------------------------|-----------------------|----------------------|-------------------|----------------------------------|
| $v = 1, J = 1–0$ (43.1 GHz) | -59.281 | -26.069 | $13.63 \pm 0.37$ | 21.40 ± 0.58 | 13.14 18:08:04.0457308 -22:13:26.626069 |
| $v = 2, J = 1–0$ (42.8 GHz) | -58.898 | -26.675 | $13.31 \pm 0.73$ | 20.90 ± 1.15 | 12.90 18:08:04.0457584 -22:13:26.626675 |
| $v = 1, J = 2–1$ (86.2 GHz) | -58.940 | -26.036 | $14.10 \pm 0.11$ | 22.14 ± 0.17 | 14.08 18:08:04.0457553 -22:13:26.626036 |
| $v = 1, J = 3–2$ (129.3 GHz) | -59.384 | -26.013 | $16.08 \pm 0.81$ | 25.25 ± 1.27 | 15.52 18:08:04.0457234 -22:13:26.626013 |
| Four SiO masers | -58.720 | -26.104 | $14.25 \pm 0.58$ | 22.37 ± 0.91 | — 18:08:04.0457712 -22:13:26.626104 |

$^a$The offset value represents the position difference of the central star with respect to the observed Hipparcos coordinates (Method).

$^b$The astronomical unit (AU) was calculated using the distance of 1.57 kpc for VX Sgr\textsuperscript{22}.

$^c$The coordinates are converted from the observed Hipparcos coordinates based on the R.A. and Dec. offsets.
masers in the SiO star. In addition, the ring radius of 129.3 GHz maser increases via the
at large opacities, spontaneous de-excitation of the SiO molecule higher rotational transitions\(^25\). This is possible even for radiative photons corresponding to the
function of the stellar phase in the 129.3 GHz maser was assumed that the masing regions of higher rotational transitions \(^4\) originate from the difference in their excitation conditions as discussed below.

**Pumping mechanism for the 129.3 GHz SiO maser.** We assumed that the masing regions of higher rotational transitions would be closely related to the optical depth of the circumstellar envelopes. The SiO maser population inversion (whether radiatively or collisionally pumped) is caused by self-trapping of photons corresponding to the \(\Delta \nu = 1\) ro-vibrational transition\(^27\). At large opacities, spontaneous de-excitation of the SiO molecule via the \(\Delta \nu = 1\) ro-vibrational transition becomes more difficult at higher rotational transitions\(^25\). This is possible even for radiative pumping in flattened regions such as in thin shells, which can be optically thick tangentially and thin radially. Thus population inversion and amplification of the higher rotational transition SiO masers is favored at progressively higher radii. Our results show a greater increase in radii and other differences between \(J = 3–2\) and \(J = 2–1\) masers, compared with those between \(J = 2–1\) and \(J = 1–0\) (Figs. 3 and 4). Thus the higher rotational transition masers in the SiO \(v = 1, J = 1–0, J = 2–1, J = 3–2\) maser lines seem to arise further from the central star. However, we cannot exclude the radiative models including line overlap\(^25\) for the further distance of the SiO \(v = 1, J = 3–2\) maser from the central star. In addition, the ring radius of 129.3 GHz maser increases near optical maximum as shown in Fig. 4, which displays the ring radius variation of the 129.3 GHz maser at multiple epochs. This fact directly supports the radiative pumping for the 129.3 GHz maser and also suggests that the radiative pumping is more dominant than the collisional pumping in the higher \(J = 3–2\) rotational transition for VX Sgr differently from the \(J = 2–1\) maser.

**Discussion**

In the viewpoint of the collisional pumping of SiO masers caused by shocks, one can expect to trace the outward shock propagation near the photosphere\(^28\) to the dust-forming layers based on the fact that the higher rotational transition masers arise further from the central star. As a future work, monitoring observations of the 129.3 GHz SiO maser together with 43.1 and 86.2 GHz SiO

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**Fig. 3** Registered maps of the SiO maser spots and the histograms of their radial distributions. The blue, red, yellow, and cyan colors indicate 43.1, 42.8, 86.2, and 129.3 GHz SiO masers, respectively. The dotted circle shows the result of ring fitting using all the maser spot distributions of the four maser lines. The mark "x" indicates the ring fitting center assumed to be the position of the central star. Histograms represent the radial distribution of the maser spots with respect to the central star. The ring radius and FWHM derived from the Gaussian fitting are represented in each panel.

**Fig. 4** Variation of the SiO ring radius with the optical light curve (in press manuscript\(^14\)). The gray cross indicates the optical light curve from American Association of Variable Star Observers (AAVSO; https://www.aavso.org). Color symbols indicate the SiO maser ring radius according to the different transitions and epochs. Cyan triangle, yellow square, blue circle, and red inverted triangle are in the order of 129.3, 86.2, 43.1, and 42.8 GHz SiO maser lines (Table 1, Supplementary Tables 2 and 4)
masers will allow us to trace the stratification structure of the excitation conditions, and inward/outward motions of maser clumps in different regions possibly associated with local shock and inhomogeneous dust formation.

Finally, our simultaneously astrometrically registered maps of the SiO and H2O masers will provide important observational constraints for the local difference in the efficiency of radial acceleration through radiation pressure on grains and the cause of the irregular appearance of the 22.2 GHz H2O masers above the dust-formation layers. In addition, the variation of the 129.3 GHz SiO ring radius with the optical light curve suggests that radiative pumping is dominant in the red supergiant VX Sgr.

Methods

KVN observations. Simultaneous VLBI monitoring observations of H2O 6–5, 3(22.235080 GHz), SiO ν = 1, 2; J = 1–0; SiO ν = 1, 2; J = 2–1; (43.122800 GHz, 42.820587 GHz, 86.243442 GHz, and 129.363359 GHz) maser lines were performed toward VX Sgr, one of the KVN key science projects29. The observations were carried out every 2 months from 2014 November to 2017 May. Here we report the observations on March 27, 2016 (ν = 0.67), which show the successful 4-band non-integer SFPR maps and those of 4 epochs, which show the single-band map of 129.3 GHz SiO maser (March 14, 2015, November 28, 2015, December 30, 2015, and December 30, 2016). The observed coordinate of VX Sgr is R.A. = 18:08:04.05, Dec. = −22:13:26.6 from Hipparcos main catalog30. The passed signal is recorded onto the 1 GHz Mark 5B (MKSB) recorder with 16 base band channels (BBCs) and 16 MHz bandwidth (512 channels) for each. We set the delay calibrator in the desired direction. The delay calibrator was then measured, and the velocities and arrangements are randomly in order to avoid high side peaks. Recorded data were correlated by the Distributed FX31,32 software correlator. The synthesized beam size, position angle, and system noise temperature obtained from the observation for each frequency are listed in Supplementary Table 1.

We used fringe finder and continuum delay calibrator sources J1743–0350 and J1833–2103, respectively. Observations were performed over 5 h with 2 min scans for the target to continuum delay calibrator. Fringe calibrator source position was measured every 1 h to exclude an instrumental delay and bandpass calibration. Amplitude calibration was done from the Astronomical Image Processing System (AIPS) task APCAL. The system noise temperature and gain variation data are available. There are no bright continuum delay calibrators stronger than 500 mJy (recommend for observations using 1 GHz recording mode in KVN) and a separation angle within 4° from VX Sgr. Our delay calibrator J1833–2103 is strong but it has a complicated structure of a gravitational lensing33 and 6.06° separation angle within 4° from VX Sgr. Another astrometrically registered map for comparison

SFPR data reduction. The data reduction was performed using the AIPS package. Basic data treatment followed the standard procedure for the phase-referencing line imaging method in the K band34. First, we used the bright fringe finder to remove the residuals of large group delays and delay rates in the target itself. Second step is to trace the residuals of fringe phases using a nearby continuum delay calibrator, whose solutions were applied to the visibilities of the target. This step enables us to compensate for large and rapidly changing phase errors during the observations. We imaged the continuum delay calibrator using DIFMAP34 in order to produce a source brightness model composed of CLEAN component. This was used in the AIPS task FRING to find the multi-band group delay andphase residuals.

The method consisted of transferring the multi-band delay solutions of the continuum delay calibrator and the phase rate solution of a strong H2O maser channel, which is copied from the K band to the calibration solutions of the SiO masers at high frequency band. The solutions were multiplied by the ratio between low and high frequency maser. This method is the basis of non-integer SFPR. The main point of the SFPR and non-integer SFPR method is transferring the low frequency phase solution to the high frequency.11–13 Non-integer SFPR enables to make high frequency VLBI images for maser lines, even though a continuum delay calibrator is weak at the high frequency. We adopted a signal-to-noise threshold of maser spot identification to be 5–10, dependent on the image noise level29, in the AIPS task SAD.

Another astrometrically registered maps for comparison. The monitoring results of February 27, 2016 (ν = 0.63) 1 month prior to March 27, 2016 (ν = 0.67) are presented in Supplementary Figs. 1, 2, 3 and Supplementary Table 2. The basic observation set-up is the same, and the system noise temperature at the K, Q, W, and D bands were up to 130, 200, 300, and 450 K. The results of the registered integrated velocity-intensity map at February 27, 2016 is shown in Supplementary Fig. 1. We could not obtain the 129.3 GHz SiO maser image because the fringe solution was not obtained at this epoch. The velocity–position maps for each

frequency maser are represented in Supplementary Fig. 2. The flux of the single dish and VLBI were about 1.5 times stronger at 43.1 and 42.8 GHz, but the morphologies on the spot distribution was similar to that of March 27, 2016 (ν = 0.67). The 86.2 GHz maser shows a stronger flux than that of 43.1 and 42.8 GHz masers at both two epochs.

The SiO maser ring fitting results are shown in Supplementary Table 2. The size distribution tendency of each frequency radii was the same within the error range of March 27, 2016 (ν = 0.67) and 129.3 GHz SiO maser. Supplementary Fig. 3 shows the registered map of the SiO masers and the spot distribution histograms from the center of the fitting in each maser line. The 42.8 GHz SiO maser located at the innermost region, and the 86.2 GHz is at the outermost region. The stellar position differences derived from the ring fitting center using all SiO maser spots is R.A. = 1.23 and ADel = −0.23 mas between these two observations (Table 1 and Supplementary Table 2).

Recovering fluxes. Figure 2 and Supplementary Fig. 2 include the spectra of the VLBI total power and recovered flux (dotted and dashed lines) together with a single-dish (solid line) spectra obtained from the closest date to the VLBI observations. Because the beam size of the VLBI is very narrow compared to that of the single dish, there is a missing flux in the VLBI observations. Also, the different baseline reversal method causes flux difference between the VLBI total power and single-dish spectra. In the case of a single-dish observation (position-switching mode), we observe the empty sky to remove the baseline from the target spectrum. On the other hand, the VLBI is calibrated using bandpass data obtained from fringe less observations.

Moreover, the maser clumps with a larger angular size compared to the VLBI beam are resolved out in the cross-correlated spectra (recovered flux). The ratios of the VLBI total power to single-dish flux and recovered values (the ratio of recovered to total power fluxes) are listed in Supplementary Table 3. In order to get the SiO maser, the 42.8 GHz high recovery values seem to originate from a more compact maser spot in the 42.8 GHz maser than that in the 43.1 GHz maser.

Astrometric uncertainty. Our registered maser maps consist of the conventional PR maps of the H2O maser, with respect to J1833–2103, and SFPR maps of the SiO masers, with respect to the H2O maser positions determined from the PR maps. As those observations need to analyze the astrometric uncertainty, we estimated the proper motions and distances of the target and delay calibrator. This could be improved by including geodetic blocks or using GPS data to reduce the residual zenith path-length error.

Ring fitting of the SiO masers. We fitted the SiO maser ring structure of 43.1, 42.8, 86.2, and 129.3 GHz maser lines using the least-squares fitting method by adopting the IDL online procedure “imfitellipse.pro” (http://cow.physics.wisc.edu/~craigm/idl/idl.html). We did not apply the weights function because we assumed that the SiO maser is a perfect circular structure. Smallest chi-square error was selected as the best fitting result. The ring fitting results were expressed as a single center position with the ring radius range. The results of the estimated ring fitting uncertainty are listed in Table 1 and Supplementary Table 2.

Four single-band maps of the 129.3 GHz SiO maser. We also detected the 129.3 GHz SiO maser at four epochs: March 14, 2015 (ν = 0.61), November 28, 2015

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Data availability. Raw data were generated at the Korea-Japan Correction Center (KJCC) in Daejeon. Derived data supporting the findings of this study are available from the corresponding author on request.

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Author contributions
S.-H.C. led the overall project. D.-H.Y. (dhysgr@gmail.com) reduced the data assisted by Y.Y. and R.D., and wrote the manuscript with reviews by S.-H.C. and H.L.Y.K.C., M.R., J.K., D.K., and H.Y. performed data verification. D.-Y.B. provided advice for the 4 band
VLBI system setting and observations. All authors discussed the data analyses and the results and commented on the manuscript.

**Additional information**

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