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LETTER

*Letter to the Editor*

# Detection of compact water maser spots around late-type stars

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**Abstract.** We observed water masers around 21 late type stars using very long baseline interferometry (VLBI) composed of 6-m telescope at Kagoshima and 10-m telescope at Mizusawa, Japan. Despite the fairly long baseline (1300 km) and the low sensitivity, we detected compact water masers around three semiregular variables R Crt, RT Vir and RX Boo and two supergiants VY CMa and VX Sgr. Detection of the stellar water masers around nearby semiregular variables at about 100 pc implies the very compact size of these maser spots of the order of $10^{12}$ cm, considerably smaller than the widely accepted typical size for stellar water masers. Almost all the line profiles of the water masers detected at the first epoch changed dramatically at the second epoch after six months. However, some strong emission peaks were detected in the same velocity at both epochs, suggesting that the lifetime of the strong maser spots is longer than six months.

**Key words:** Masers – star:late type – star:mass-loss

## 1. Introduction

Water masers around late type stars as observed with the high spatial resolution of VLBI are expected to be ideal tracers of detailed physics and kinematics in the mass-loss process of late type stars (e.g. Elitzur 1992; Takaba et al. 1994), as well as good position indicators of stars for studying the dynamics of the Galaxy (Sasao & Morimoto 1991). However, the VLBI detectability of the stellar water masers criticallydepends on the size of the maser spots. Lifetime of the maser spots is also an important factor to monitor the property of the stellar water masers and to measure their proper motions.

Spots of stellar water masers have the typical size of $10^{13}$ cm (Reid & Moran 1981). For example, Spencer et al. (1979) measured the spot size and obtained the size values of 1.6–2.7 milliarcseconds around several late type stars (RT Vir, W Hya, RX Boo, R Aql, and RR Aql), which correspond to the linear size of 0.5–1.8 $\times 10^{13}$ cm. At the same time, the stellar water masers were often resolved out with baselines longer than 1000 km (Moran et al. 1973). Taking into account the sparseness of the previous VLBI surveys on the stellar water masers, it is worthwhile to search for more compact water maser spots using the present VLBI technology.

The lifetime of the stellar water masers has not been well determined due to the lack of systematic VLBI surveys and monitorings. According to the VLA observations by Bowers et al. (1993), the spatial distribution of water masers around W Hya changed completely during five years, in spite of the apparently similar line profiles as shown by the single-dish observations (Engels et al. 1988; Szymczak & Engels 1995). It is therefore interesting to check whether the maser lines are stable in the VLBI cross-power spectra where only the very compact maser spots are present.

In our VLBI survey, we examined the detectability and the line stability of strong stellar water masers using 1300 km baseline between Kagoshima and Mizusawa, which is longer than the Haystack–Greenbank baseline (845 km) used in the previous VLBI surveys (e.g. Spencer et al. 1979).

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**Table 1.** List of the water maser sources observed in the present VLBI observations

| Object name | Stellar type | R.A. (B1950) | Dec. (B1950) | Distance | $V_{LSR}(H_2O)$ | $S_{peak}(H_2O)^a$ |
|---|---|---|---|---|---|---|
| | | h m s | ° ' " | pc | km s$^{-1}$ | Jy |
| S Per | Supergiant | 02 19 16.0 | +58 21 18.0 | 2300 | -45.48 | 135 |
| IK Tau | Mira | 03 50 43.8 | +11 15 31.7 | 270 | – | – |
| IRC60154 | – | 05 15 05.0 | +63 12 54.0 | – | – | – |
| U Ori | Mira | 05 52 51.0 | +20 10 06.0 | 246 | – | – |
| IRC60169 | Mira | 06 30 00.6 | +60 58 54.0 | – | -33.32 | 115 |
| VY CMa | Supergiant | 07 20 54.7 | −25 40 12.6 | 1500 | 17.06 | 9188 |
| X Hya | Semiregular | 09 33 06.9 | −14 28 02.0 | 70 | – | – |
| R Leo | Mira | 09 44 52.6 | +11 39 44.0 | 162 | – | – |
| R Crt | Semiregular | 10 58 06.0 | −18 03 21.0 | 110 | 3.47 | 487 |
| S Crt | Semiregular | 11 50 11.7 | −07 19 06.6 | 260 | – | – |
| RT Vir | Semiregular | 13 00 06.1 | +05 27 14.0 | 120 | 11.84 | 628 |
| W Hya | Semiregular | 13 46 12.1 | −28 07 08.5 | 100 | 41.32 | 177 |
| RU Hya | Mira | 14 08 42.0 | −28 38 24.0 | 741 | – | – |
| RX Boo | Semiregular | 14 21 56.8 | +25 55 48.4 | 130 | 3.36 | 1254 |
| RS Vir | Mira | 14 24 46.0 | +04 54 09.0 | 613 | – | – |
| U Her | Mira | 16 23 34.9 | +19 00 18.0 | 390 | -16.05 | 118 |
| VX Sgr | Supergiant | 18 05 03.0 | −22 14 00.0 | 1500 | 12.95 | 1166 |
| R Aql | Mira | 19 03 57.7 | +08 09 10.3 | 170 | 48.16 | 313 |
| RR Aql | Mira | 19 55 00.3 | −02 01 17.1 | 527 | 28.52 | 296 |
| NML Cyg | Supergiant | 20 44 33.8 | +39 55 57.2 | 1800 | -19.57 | 357 |
| TW Peg | Semiregular | 22 01 41.0 | +28 06 30.0 | – | – | – |

[a]Maximum total-power flux density at epoch January 17-20, 1995

## 2. Observations

VLBI survey observations were conducted at two epochs: June 17–18, 1994, and January 17–18 and 20, 1995, with two telescopes of National Astronomical Observatory (NAO), Japan: the 6-m telescope at Kagoshima (Omodaka et al. 1994) and the 10-m telescope at Mizusawa (Shibata et al. 1994a). The baseline length is 1297 km corresponding to the minimum fringe spacing of 2.1 milliarcseconds at 22 GHz. The system noise temperatures of 6-m and 10-m telescopes at zenith were 200 K and 380 K at the first epoch, and 180 K and 160–280 K at the second epoch, respectively. We used the K-4 VLBI backend system (Kiuchi et al. 1991) which has 16 video channels with 2 MHz bandwidth each. The VLBI recorded data were cross- and auto-correlated using New Advanced One-unit COrrelater (NAOCO) (Shibata et al. 1994b) at Mizusawa Astrogeodynamics Observatory/NAO. The 512 complex lags of NAOCO yielded velocity resolution of 0.106 km s$^{-1}$ in the cross-power spectrum and 0.053 km s$^{-1}$ in the total-power spectrum.

We observed 21 late type stars and the sources are listed in Table 1. The sources were scaned 2–5 times with duration of 400–1200 seconds. The integration time of the cross-correlated data was set to 300 seconds which gives the fringe-rate resolution corresponding to minimum spatial resolution of 70 milliarcseconds. Since the stellar water masers we surveyed are known to distribute within the scale smaller than 100 milliarcseconds (e.g. Bowers & Johnston 1994), most of the water masers must be in the same fringe-rate channel containing the strongest maser emission peak. We calibrated the cross-power spectra for the bandpass characteristics and the temporal variability of antenna gains following Diamond (1989). The accuracy of the estimated flux density was 20 % for the total-power spectrum and 30–40 % for the cross-power spectrum, respectively. The detection limits at 5 $\sigma$ level in total-power spectra and in cross-power spectra were 100 Jy and 200 Jy at the first epoch and 50 Jy and 100 Jy at the second epoch, respectively.

## 3. Results and Discussion

Out of 21 late type stars observed, the water maser emission was detected in the total-power spectra of both telescopes from 12 stars and, among them, from five stars in the cross-power spectra. Here, the line profiles of only two sources out of five above are shown in Fig. 1. Their basic characteristics are listed in Table 2.

Most of the maser emission detected in the cross-power spectra were partially resolved with our VLBI baseline. Assuming Gaussian distribution of the brigthness, we roughly estimated the size of the water maser spots from their visibility (ratio of cross-power flux density to total-power flux density). We obtained the size value of 0.3–1.2 milliarcseconds. Moreover, we scanned two strong maser components around RT Vir five times at the second epoch to investigate the relation between the visibility and the projected baseline length (see Fig. 2). The result shows no trend of decreasing visibility of the maser components with increasing projected baseline length from 800 km to 1280 km within the estimation error. Thus, the components

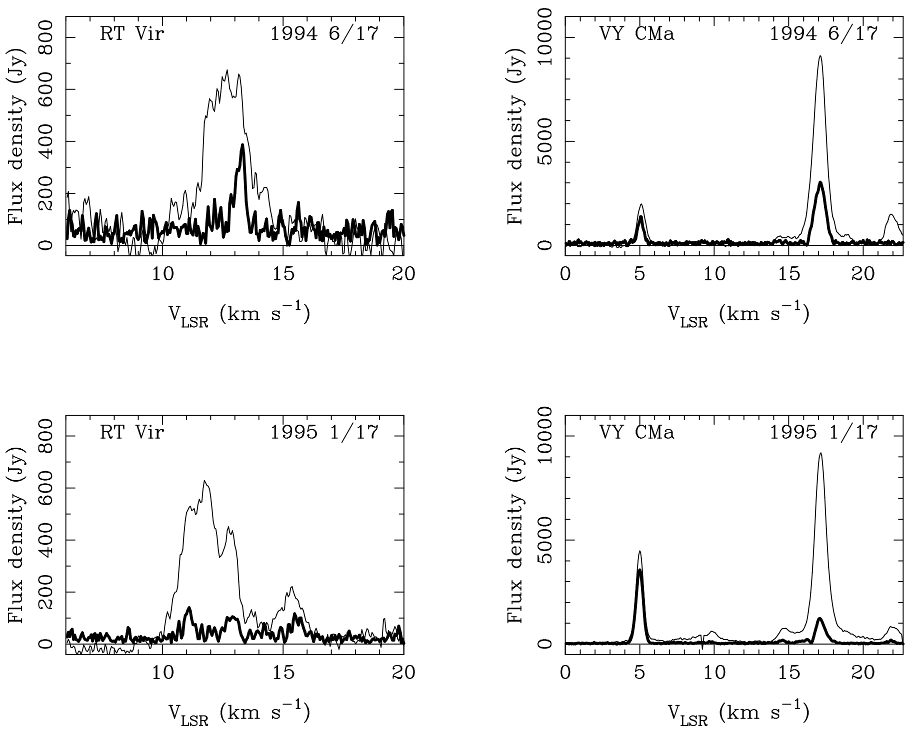


**Fig. 1.** Line profiles for observed stellar water masers in the total-power spectra of Mizusawa 10m telescope (thin line) and the cross-power spectra (heavy line) at two epochs.

were not resolved significantly by the 2 milliarcsecond beam of our VLBI observations.

These results show that there are compact water maser spots smaller than 1 milliarcsecond. In particular, three semiregular variables R Crt, RT Vir and RX Boo are estimatied to be at the distance of 100–200 pc (e.g. Szymczak & Engels 1995). Therefore, the maser spots associated with the three stars must be very compact with the size smaller than $3.3 \times 10^{12}$ cm. The size value is considerably smaller than the widely accepted typical value for the stellar water masers (roughly $10^{13}$ cm, Reid & Moran 1981).

On the other hand, several maser components were not detected in the cross-power spectra despite their large enough total-power flux density. For example, total-power flux density of the water masers around W Hya at the first epoch was about 700 Jy, though they showed no peak in the cross-power spectra. A half of the masers we identified in the total power spectra were in this case. In particular, no water maser was detected in the cross-power spectra from Mira variables. It is likely that they are fairly larger than $10^{13}$ cm and accordingly resolved out by our 1300 km VLBI baseline.

We also note that the water masers around supergiants VY CMa and VX Sgr tend to be more stable than those around semiregular variables R Crt, RT Vir and RX Boo. The water masers around VY CMa and VX Sgr show very similar line profiles in the total-power spectra at the two epochs. In case of VY CMa, the profiles in the cross-power spectra are also similar at the two epochs. On the other hand, the line profiles of the water masers around the semiregular variables changed dramatically during two epochs. Several weak components in the same source turned on or off at times. The maser emission

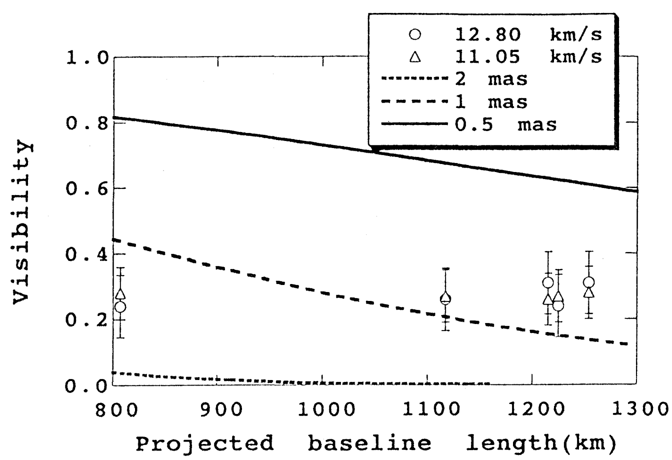


**Fig. 2.** Plots of visibility (ratio of the cross-power flux density to the total-power flux density) for two water maser spots detected around RT Vir at epoch January 17–20, 1995. Gaussian slopes for the source sizes of 0.5, 1.0 and 2.0 milliarcseconds are also shown for comparison.

around RX Boo is its extreme case (see Table 2). The similar tendency was reported earlier by Engels et al. (1988) on the basis of their single-dish survey.

On the other hand, there are several strong velocity components which are detected in the same velocity within the typical velocity width of 0.5 km $s^{-1}$ in the cross-power spectra and apparently survived by six months between two observing epochs. However, there is a case when the maser line around RT Vir with $V_{LSR}$ = 13.32 km $s^{-1}$ shows a slight shift in velocity of 0.4 km $s^{-1}$. (see Table 2). In this particular case, careful examination is needed to judge that the maser lines detected at two epochs

**Table 2.** Comparison of the peak velocities of water maser spots at epochs June 17-18, 1994 and January 17-20, 1995

| Object name | 1994 June 17 Peak $V_{LSR}$ | Line width (FWHM) | Cross-power flux density | Projected baseline length | Visibility[a] | 1995 January 17-18 Peak $V_{LSR}$ | Line width (FWHM) | Cross-power flux density | Projected baseline length | Visibility[a] |
|---|---|---|---|---|---|---|---|---|---|---|
| | km s$^{-1}$ | km s$^{-1}$ | Jy | km | | km s$^{-1}$ | km s$^{-1}$ | Jy | km | |
| VY CMa | 5.05 | 0.43 | 1383 | 1195 | 0.71 | 5.00 | 0.58 | 3564 | 704 | 0.81 |
| | 17.11 | 0.85 | 3037 | 1195 | 0.33 | 17.06 | 0.69 | 1226 | 704 | 0.14 |
| R Crt | | | Not detected | | | 9.79 | 0.63 | 209 | 760 | 0.61 |
| RT Vir | | | | | | 11.11 | 0.48 | 140 | 1117 | 0.27 |
| | 13.32 | 0.42 | 387 | 984 | 0.72 | 12.90 | 0.58 | 105 | 807 | 0.24 |
| | | | | | | 15.48 | 0.63 | 117 | 1215 | 0.63 |
| RX Boo | | | Not detected | | | 3.26 | 0.53 | 498 | 1282 | 0.40 |
| VX Sgr | | | | | | -0.85 | 0.53 | 119 | 659 | 0.19 |
| | | | | | | 5.58 | 0.42 | 136 | 659 | 0.19 |
| | | | | | | 6.58 | 0.79 | 158 | 659 | 0.27 |
| | 13.05 | 0.53 | 331 | 1011 | 0.35 | 13.05 | 0.54 | 568 | 659 | 0.49 |

[a]Ratio of cross-power flux density to total-power flux density

belong to the same spot. The final answer about the lifetime of the maser spots should await detailed tracing of the spatial distribution of the individual maser spots at several epochs.

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