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LETTER

Letter to the Editor

Measurement of shifts in line-of-sight velocities of stellar water masers using VLBI

H. Imai[1,2], K. M. Shibata[2], T. Sasao[2], M. Miyoshi[2], O.Kameya[2], T. Omodaka[3], M. Morimoto[3], T. Iwata[4,5], T. Suzuyama[6], N. Mochizuki[3,7], T. Miyaji[8], and M. Takeuti[1]

[1] Astronomical Institute, Graduate School of Science, Tôhoku University, Aoba, Sendai, 980-77, Japan
[2] Mizusawa Astrogeodynamics Observatory, National Astronomical Observatory, 2-12, Hoshigaoka, Mizusawa, Iwate, 023, Japan
[3] Department of Physics, College of Liberal Arts, Kagoshima University, 1-21-3, Korimoto, Kagoshima, 890, Japan
[4] Kashima Space Research Center, Communications Research Laboratory, 893-1, Hirai, Kashima, Ibaraki, 314, Japan
[5] Office of Satellite Systems, National Space Development Agency of Japan, 1-29-6, Hamamatsu-cho, Minato-ku, Tokyo, 105, Japan
[6] Faculty of Engineering, Kasoshima University, 1-21-3, Korimoto, Kagoshima, 890, Japan
[7] Department of Physics, Faculty of Science, Kagoshima University, 1-21-3, Korimoto, Kagoshima, 890, Japan
[8] Nobeyama Radio Observatory, National Astronomical Observatory, Nobeyama, Minamimaki, Minamisaku, Nagano, 384-13, Japan

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Abstract. We performed VLBI monitoring observations of water masers around a semiregular variable RT Vir and detected for the first time systematic shifts of line-of-sight velocities in time for several spatially distinguished water maser spots. In some strong water maser spots, the line-of-sight velocities linearly increased or decreased through successive observing sessions during four months. The rates of the velocity shifts ranged from -3.55 to 1.76 km $s^{-1}yr^{-1}$. We also noted that the blue-shifted and red-shifted maser components with respect to the stellar velocity are clearly separated in the celestial plane. If mass-loss process of the evolved star is described with simple kinematic models like bipolar flow or rotation disk, we should find one-to-one correspondence between acceleration/deceleration and blue-shift/red-shift of the maser spots. However, we did not find such a clear correspondence. The fact is likely to imply the more complicated nature of the real mass-loss process of the evolved star.

Key words: Masers – stars:late-type – stars:mass-loss

1. Introduction

Stellar water masers as observed with the high spatial resolution of VLBI are expected to be very useful tracers of detailed physics and kinematics in the mass-loss process of evolved stars (e.g. Elitzur 1992; Takaba et al. 1994).

Send offprint requests to: H. Imai(E-mail: imai@miz.nao.ac.jp)

Previous VLA observations revealed that the stellar water masers distribute in circumstellar shells with radii ranging from about 5–10 to 50–100 AU in Mira and semiregular variables (Lane et al. 1987; Bowers & Johnston 1994, hereafter BJ). Benson et al. (1992) and BJ found periodic variations of the water masers correlated with the optical light curves in intensity and spatial distribution, respectively. Bowers, Claussen & Johnston (1993, hereafter BCJ) as well as BJ pointed out that the angular distributions of the water masers are often significantly asymmetric relative to the estimated stellar position. Although the velocity field of the masers is generally consistent with the expanding shell model, the expansion is not strictly isotropic. In some cases, we observe clear anisotropy suggestive of weakly bipolar outflow (BJ). Yates & Cohen (1994, hereafter YC) and BJ suggest that the material in the masing region is accelerated to the terminal velocity of about 10 km s^{-1} at radii ranging from several to a few tens of AU.

In the light of the above rather complicated appearance of the circumstellar environment including the water masers, it is quite interesting to directly detect the acceleration of the maser spots. Having information on positions, velocities and accelerations of the maser spots, we will be able to greatly constrain the underlying dynamics of the mass-loss process. The simplest way to detect the acceleration is to measure shifts of the line-of-sight velocities in time for the maser spots, which are known to be very compact with apparent sizes of the order of 0.1 to 10 milliarcseconds (mas) (Spencer et al. 1979; Imai et al. 1997). However, tracing the velocity shifts is sometimes difficult since several maser spots are often blended within a single peak in the velocity profile obtained from single-dish observations (Sullivan III 1971, 1973; BCJ; BJ; YC). Therefore, higher spatial resolution is indispensable to trace the velocity shift of each spatially-well-distinguished spot.

Here we report first measurement of the linear shifts of line-of-sight velocities for water maser spots associated with a semiregular variable RT Vir obtained in a VLBI monitoring using Japanese domestic network called J-Net.

2. Observations and data analysis

We conducted VLBI monitoring from January to May in 1996 using J-Net, composed of three telescopes of National Astronomical Observatory, Japan, 10-m telescope at Mizusawa, 45-m telescope at Nobeyama and 6-m telescope at Kagoshima, as well as 34-m telescope belonging to Communications Research Laboratory at Kashima. Performance parameters of the telescopes and epochs of the observations are shown in Tables 1 and 2, respectively. The minimum fringe spacings of the baselines ranged from 2.1 to 14 mas at 22.2 GHz. We used the K-4 backend system (Kiuchi et al. 1991) which has 16 video channels with 2 MHz bandwidth each. The VLBI data were cross- and auto-correlated by using New Advanced One-unit COrrelator (NAOCO) (Shibata et al. 1994) at Mizusawa Astrogeodynamics Observatory/NAOJ. The 512 complex lags of NAOCO yielded high velocity resolution of 0.106 km s^{-1} in the cross-power spectrum and 0.053 km s^{-1} in the total-power spectrum at 22.2 GHz. We used the multiple fringe-rate mapping method (Walker 1981) to obtain wide-field map of the masing region. First, we selected a velocity channel containing a single maser spot as phase reference based on comparisons between temporal variations of cross-power flux density and gain curves of the baselines. The baseline gain curves were obtained from the auto-correlated data which were calibrated with respect to the frequency-band characteristics following the method presented in Diamond (1989). A velocity channel showing the temporal variation of the cross-power flux density very similar to that of the baseline gain curve was selected as containing a single spot of simple structure. Second, the VLBI data were integrated in the phase-referenced mode for 1200 seconds. The integration time provides appropriate number of $(\dot{u}, \dot{v})$ data sets with sufficiently high S/N ratios (approximately 10 Jy at 5σ level) and spatial resolution (approximately 25 mas in right ascention). We thus obtained the fringe-rate maps with relative position accuracy of 5 to 15 mas in right ascenstion and 10 to 50 mas in declination in the single velocity channel.

We carefully identified spatially-distinguished water maser spots and measured their line-of-sight velocities. We first picked up those maser components in the successive velocity channels which are confined within the possible range of the position error (15 mas in right ascention and 100 mas in declination) and regarded them as originating from a single maser spot. The line-of-sight velocity of the maser spot was estimated at the flux peak of the maser spot. Accuracy in determining the velocity was estimated to be 0.1 to 0.2 km s^{-1} based on measured changes of flux peaks during a day due mainly to the random noise. Then we regarded the maser spots which existed in the same relative position through the successive epochs within the accuracy in position determination as the same maser spot. Such a procedure was safely performed for the stronger maser spots which are well determined in the relative position, especially, in right ascention.

Table 1. Performance parameters of the participating telescopes in J-Net

J-Net Telescope		Diameter	Aperture Efficiency	T_{sys} at zenith
		m	%	K
Mizusawa	(M)	10	36	140 – 330
Kashima	(S)	34	5 [a]	280 – 340
Nobeyama	(N)	45	63	240 – 290
Kagoshima	(K)	6	40	170 – 220

[a] Usually 57 % , but in extraordinary low level during our observations due to instrumental problems

Table 2. Observing epochs in our J-Net observations and the participating telescopes

Epoch (1995)	Time(UT)	Telescopes
January 17	– [a]	M, K
February 21	15:00 – 23:00	M, K
February 28	14:20 – 22:30	M, S, K
April 6	10:50 – 18:40	M, S, N, K
May 9	08:10 – 16:30	M, S, N, K

[a] Snapshot observation by Imai et al. (1997)

3. Results and discussion

RT Vir is a semiregular variable (SRb) at the estimated distance between 120 pc (Szymczak & Engels 1995) and 460 pc (Menten & Melnick 1991). RT Vir is surrounded by strong water masers with flux density steadily greater than 100 Jy.

The distribution of the water masers at epoch April 6, 1995 is shown in Fig. 1. The figure demonstrates that the distribution size of water masers is about 160 mas in right ascention, which is roughly twice as large as those previously obtained by BCJ, BJ and YC (80–110 mas). It is interesting to investigate the relation in time variation between the distribution size of the water masers and the phase of the optical light curve. Therefore, we analyzed unpublished data of RT Vir in American Association of Variable Star Observation (AAVSO) with the phase dispersion minimization method to correctly estimate the light phase in the previous (BCJ on January 1985, YC on February 1985, and BJ on December 1988) and the present observations (January–May 1995). The analysis showed that the pulsation period of RT Vir is 375 days and that the previous observations were near the light maxima and the present observations are vice versa. Thus, the distribution size of the water masers are likely to be correlated with the optical light curve in such a way that the distribution

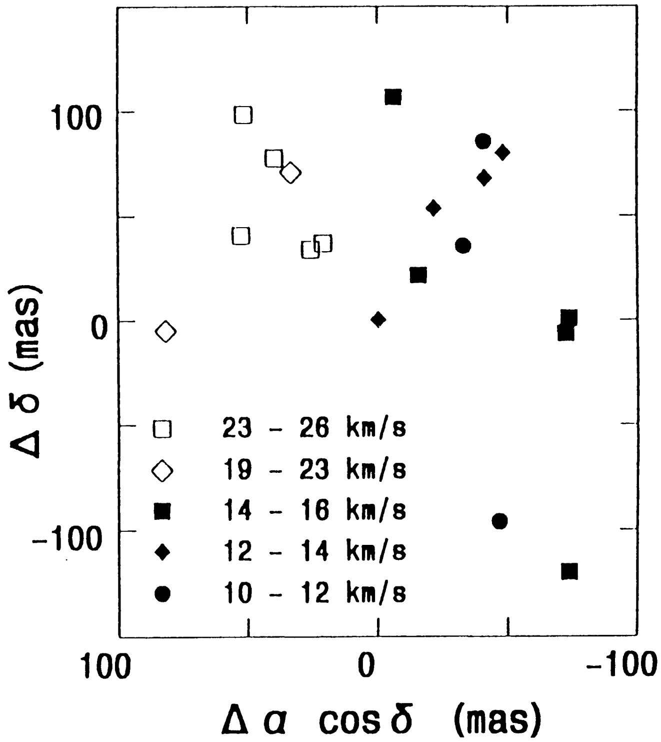

Fig. 1. Spatial distribution of detected water masers around RT Vir on April 6, 1995. The shown position is that of the cross-power flux peak of each individual maser spot. The relative position errors are 5–15 mas in right ascention and 10–50 mas in declination. The stellar velocity is estimated to be 17–18 km s^{-1}(e.g., BJ; YC).

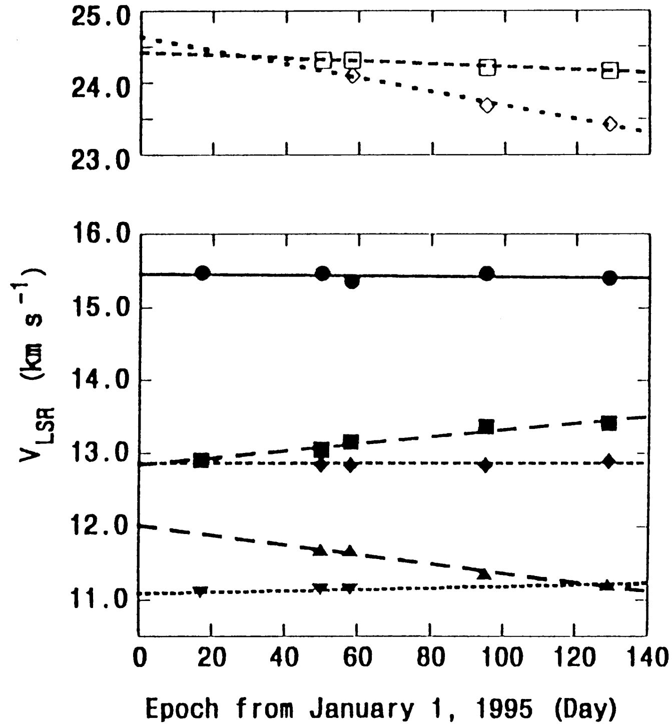

Fig. 2. Shifts of line-of-sight velocities in time of detected strong water masers around RT Vir during four months in 1995. The component V_{LSR}= 12.9 km s^{-1} at the first epoch is assumed to be a blend of two maser spots.

size is largest near the optical minimum. The similar variation of spatial structure of stellar water masers correlated with the stellar light curve was first discovered in a Mira variable R Aql by BJ, and our case of RT Vir is the second for the late type stars after R Aql and the first for the semiregular variables.

Fig. 1 also shows that the blue-shifted and red-shifted maser components with respective to the stellar velocity (17–18 km s^{-1}, e.g., BJ; YC) are clearly separated in the celestial plane. The direction of the line of separation is roughly east-west and consistent with those reported in the previous results by BCJ, BY and YC.

Fig. 2 shows measured shifts of line-of-sight velocities in time for seven water maser spots which are strong enough and well determined in spatial position. The estimated rates of the velocity shifts range from -3.55 to 1.76 km $s^{-1}yr^{-1}$ and are listed in Table 3. We could not reliably measure the velocity shifts of other maser spots because of the difficulty in identifying the same maser spot among successive observing sessions due to the limited positional accuracy in our wide-field mapping. Fig. 1. reminds more or less simple stream pattern like bipolar flow or rotation. However, it is evident from Fig. 2 that there is no clear one-to-one correspondence between acceleration/deceleration and blue-shift/red-shift of the maser spots. It is therefore difficult to reconcile the observed results to the simplest kinematical models like rotating disk or bipolar flow. Perhaps, the real mass-loss process involves a fairly complicated streaming pattern in the circumstellar space. The present results mostly preclude a rotating disk model of the masing gas. In fact, even if we disregard the mismatch between the observed and expected velocity-acceleration patterns, we still need material ejected from the surface of the slowly rotating star to acquire the rotational velocity of order 10 km s^{-1} to explain the observed velocities and accelerations in terms of rotation. Greenhill et al. (1995) also suggest that there is little rotational motion of material with SiO masers nearby the stellar surface. It is premature to attempt to draw any further physical interpretation from the newly detected velocity shifts, in view of the small number

Table 3. Rates of shifts in line-of-sight velocities in time of strong water masers around RT Vir

V_{LSR} [a]	V_{LSR} shift	
km s^{-1}	km $s^{-1}yr^{-1}$	
24.21	-0.60	± 0.19
23.68	-3.55	± 0.58
15.47	0.013	± 0.25
13.36	1.76	± 0.23
12.83	0.24	± 0.17
11.36	-2.39	± 0.24
11.15 [b]	0.082	± 0.42

[a] On April 6, 1995

[b] Not detected on April 6, 1995. The shown velocity is one on February 28, 1995.

of maser spots for which the velocity shifts are measured. Furthermore, we cannot reject yet the possibility that the shifts of line-of-sight velocities are caused only by changes in the masing region within the circumstellar clouds and might not directly reflect the real gas motions. Sullivan III (1971, 1973) claimed that the changes in line-of-sight velocities of water masers are likely to be due to changes in line strength of the three transitions within the fine structure. Therefore, more systematic and sensitive monitoring of the stellar water masers using VLBI is highly desirable for obtaining unambiguous conclusions on the newly discovered phenomena and on the mass-loss process of the evolved star. Then it is indispensable that the monitoring is performed with short time intervals from several days to one month between successive epochs because the spatial distribution of the water masers may change within the time intervals. We expect that it will be possible to measure similar velocity shifts for dozens of maser spots around RT Vir in more sensitive future VLBI observations with better mapping accuracy. Also, the high resolution VLBI monitoring will enable us to investigate transverse velocities of the maser spots and their accelerations or decelerations on the basis of proper motions of the maser spots and their time variations, which will further constrain the mass-loss dynamics of the evolved star.

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