EXPLORING STELLAR-PULSATION-DRIVEN SHOCK WAVES REVEALED IN THE KINEMATICS OF WATER MASERS AROUND RT VIRGINIS

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ABSTRACTS

We report multi-epoch VLBA observations of water masers around the semiregular variable RT Virginis (RT Vir). The 3-D kinematics of 61 maser features describes a circumstellar envelope expanding roughly spherically with a velocity of $\sim$10 km s^{-1}. Systematic radial-velocity drifts of masers were found with amplitudes of around 1 km s^{-1} yr^{-1}. From one maser feature, a quadratic position shift was discovered with an acceleration rate of 36 km s^{-1} yr^{-1}, implying a passage of a shock wave driven by the stellar pulsation. We estimated a distance to RT Virginis of $\sim$220 pc on the basis of the statistical parallax and the model-fitting methods.

INTRODUCTION

Material ejected from an evolved star gets colder and forms dust while it extends into the interstellar space. The formed dust is accelerated by stellar radiative pressure and forms an expanding envelope. However, circumstellar envelopes are not necessarily spherically symmetric. The origin of such asymmetry is likely due to anisotropic mass ejection near the stellar surface (e.g. [8]). On the other hand, shock waves are also expected, which are driven by stellar pulsation that causes periodic variation in the stellar radiative pressure to the dust. These shock waves are formed near the stellar surface and transported to larger distances from the star and generate velocity gaps by $\sim$10 km s^{-1} in front and in back of the shock waves [3]. Observations

of the anisotropic mass ejection at the early phase of evolved stars and the accelerations of the mass-loss flows due to the shock waves are important clues to demonstrating the proposed dynamical models of circumstellar envelopes and elucidating the developments of the circumstellar envelopes as a feed-back process of the material from stars to the interstellar space.
Water maser emission is seen in such circumstellar envelopes at distances of several tens of AU from Mira-type stars and consists of many of very compact features (e.g. [1]). Multi-epoch VLBI observations of H_2O masers enable the measurement of radial and proper motions of individual maser features (e.g. [7]; [6]). Furthermore, such measurements contain information on acceleration of maser features, which is caused by the pulsation-driven shock waves mentioned above.
The semiregular variable star RT Virginis (RT Vir) is one of bright H_2O maser sources (e.g. [1]; [9]). The period of stellar pulsation of RT Vir has been estimated to be $\simeq$155 days with some irregularity (e.g. [2], c.f. [5]). Radial-velocity drifts of the H_2O masers with time have been found with VLBI observations [5], however, the origin of the drifts and true maser kinematics are still clarified (c.f. [9]). Here we describe the 3-D motions and the radial-velocity drifts of H_2O masers, which have been measured more accurately with data of observations with the Very Long baseline Array (VLBA).

OBSERVATIONS

The VLBA observations had been made 5 occasions in 1998 May–August, with a separation of 3 weeks from epoch to another. Each of the observations had duration of 4 hours. The signals were received in dual circular polarization. The correlated data had spectral resolution of 0.056 km s^{-1}. An obtained synthesized beam was 0.4 mas and 1.0 mas in east–west and north–south directions, respectively. The detection limit was 100 mJy beam^{-1} at 5-σ noise level in cases without bright maser emission. Typical positional accuracy of 50 μas for a maser feature.

RESULTS AND DISCUSSION

H_2O masers in RT Vir were resolved better into individual maser features with a typical size of 1 AU with the VLBA synthesized beam than those in previous observations [5]; [9]. As a result, about 60 maser features had been detected at every observation and totally 61 maser features had been detected at least twice and measured their relative proper motions and radial-velocity drifts.

3-D Kinematics of H_2O Maser Features in RT Virginis

Fig. 1 shows obtained 3-D motions of the H_2O masers. While the H_2O masers exhibit a radial-velocity gradient in the east–west direction, the 3-D maser kinematics roughly fits a spherically-expanding flow model with a velocity of $\simeq$10 km s^{-1}. The velocity dispersion is almost equal in the whole direction within a factor of 1.7. The morphology and the kinematics of circumstellar envelopes exhibit significant bipolarity of flows in some of semiregular variables, mass-loss rates of which are relatively small ($\dot{M} \leq 10^{-6}$ $M_\odot$ yr^{-1}, [6]). On the other hand, other types of evolved stars with relatively large mass-loss rates ($\dot{M} > 10^{-6}$ $M_\odot$ yr^{-1}), except supergiants, have envelopes with spherically asymmetric morphology and kinematics. The circumstellar envelope of RT Vir ($\dot{M} \simeq 3\times10^{-6}$ $M_\odot$ yr^{-1}, [10]) is likely in the transition during the mass-loss rate increasing as it evolves and the intrinsic bipolarity of the flow get being obscured by the growing envelope.

Acceleration motions found in H_2O Maser Features

We found an H_2O maser feature in RT Vir, which exhibits an apparently acceleration motion along a straight line. Fig. 2 shows that the motions of the maser feature well fit quadratic curves in the R.A. and decl. directions, which is indicative of a constant acceleration motion. The acceleration of the feature is stronger on the sky plane ($\simeq$36 km s^{-1} yr^{-1}) than that along the line-of-sight ($\simeq$1 km s^{-1} yr^{-1}). The latter value has been obtained for other maser features and roughly equal to those found in previous observations [5]. Such a bias in an acceleration motion is expected from beaming effect of maser radiation. Strong maser amplification requests a long velocity-coherent path of molecular gas along the line-of-sight, while a large acceleration of the gas is followed by a large velocity gradient in the gas. Only large acceleration along the sky plane is

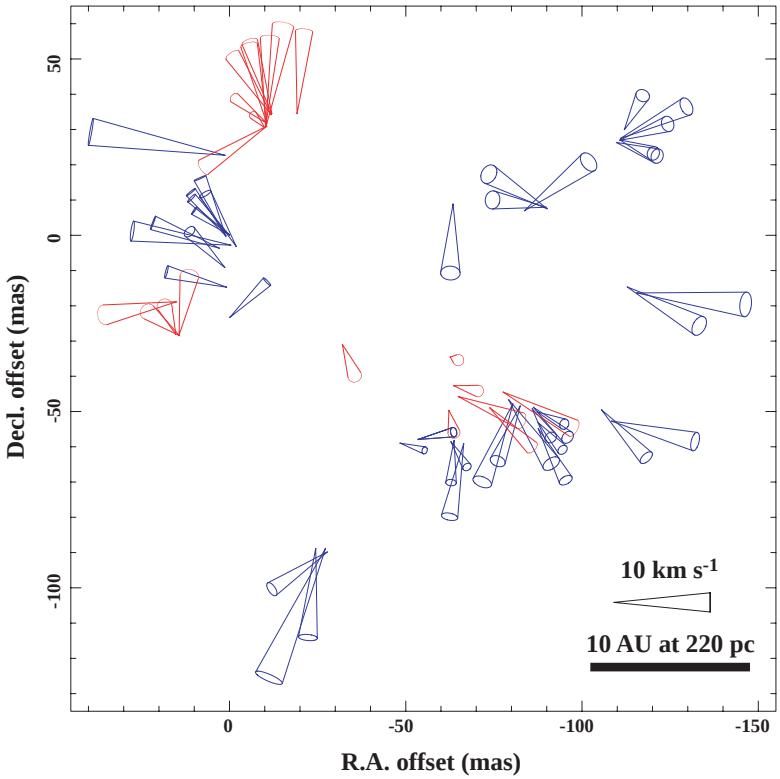

Fig. 1. 3-D velocity field of H_2O masers around RT Vir. A 3-D velocity vector of a feature is indicated by a cone. 3-D motions of 61 maser features each of which had been detected at least twice are shown. A blue and a red cones indicate an approaching and a receding features, respectively, with respect to the stellar systemic velocity ($V_{\rm LSR}\simeq$18 km s^{-1}).

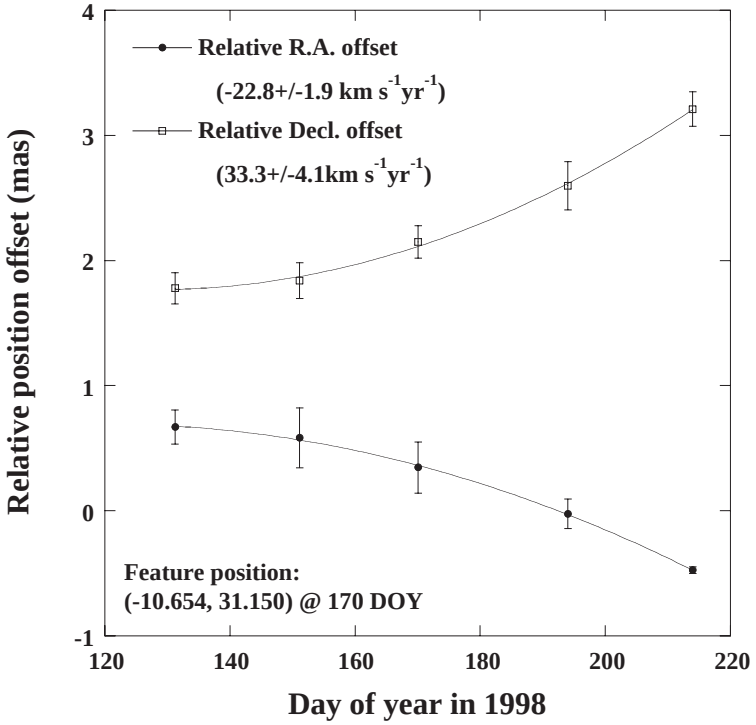

Fig. 2. Temporal position variation of a maser feature that apparently shows an acceleration motion. Solid lines indicate fits to the position variation in R.A. and decl. directions assuming a constant acceleration motion. Positions of the maser feature at individual epochs were defined to be at the brightness peak among the maser spots in the maser feature.

detectable. The detected amplitude of the acceleration of a maser feature is roughly consistent with that expected by models of the pulsation-driven shock waves [3].

Distance to RT Virginis

To directly estimate the distance to RT Vir, we applied both of the statistical parallax and the model-fitting methods assuming a radially expanding flow for the 3-D maser kinematics (e.g. [4]). These methods gave distance values of 237±29 pc and 85±12 pc, respectively, for the whole data of the proper motions. The distance estimated by the model-fitting method was underestimated because some of the maser features exhibit contractions toward the central star and contribute to underestimate of an estimated expansion velocity. On the other hand, excluding the contracting features, these methods gave distance values of 214±28 pc and 226±16 pc, respectively. These values are quite consistent with each other, and the distance value of ∼220 pc can be adopted for RT Vir.

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