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Multi-epoch VLBA observations of 7 mm SiO masers

Jiyune Yi⋆, R. S. Booth, and J. E. Conway

Onsala Space Observatory, Chalmers University of Technology, 43992, Onsala, Sweden

Abstract. We present simultaneous observations of $v\ =1$ and $v\ =2$ $J=1\rightarrow 0$ SiO masers at 43 GHz in TX Cam using the VLBA, over three different stellar phases. The spatial distribution of the two maser line emissions is considered to be a strong constraint on the modeling of circumstellar SiO maser.
We find that the separation of the masing components in the $v\ =1$ and $v\ =2$ $J=1\rightarrow 0$ changes over different stellar phases. We argue that a conclusion in favor of one maser pumping scheme based on a single epoch observation could be misleading. We also show some other evidence of stellar phase dependent properties. The disruption of a ring shape of maser distribution centered on the star is observed when the maser flux become weaken. The ring radii and the number of masing components vary depending on the stellar phase.
Our multi-epoch simultaneous observations of $v\ =1$ and $v\ =2$ $J=1\rightarrow 0$ SiO masers prove that modelings of a SiO maser pumping mechanism can be greatly benefited by this kind of work. Observations of the phase dependence properties of the SiO masers in Mira variable show clearly the need of many new high resolution experiments toward other types of evolved stars.

1. Introduction

VLBI observations of $v\ =1$ $J=1\rightarrow 0$ SiO maser toward Mira variables over the last several years have demonstrated that masing components lie within a few stellar radii of the parent star, forming a ring-like structure. Circumstellar SiO masers were predicted to occur close to the stellar photosphere inside the dust condensation layer and therefore they were suggested as a unique tracer of the innermost circumstellar envelope of AGB stars. VLBI mapping of SiO maser in $v\ =1$ $J=1\rightarrow 0$ at 43 GHz proved the prediction of its location so that we now can use the SiO maser emission as an excellent tool to study the extended atmosphere of the host star, whose mass loss leads to the last stage of its life.

Debates on the pumping mechanism of circumstellar maser emission have continued since its first interpretation made in 1974. Building a plausible SiO maser model which can be coupled with a pulsating AGB stellar model needed theoretical development but also required observational feedback. 7mm observations of SiO masers in the $v\ =1$ and $v\ =2$ $J=1\rightarrow 0$ lines can play a significant role in this regard. A standard radiative pump scheme has difficulty producing strong $J=1\rightarrow 0$ transition in both $v\ =1$ and $v\ =2$ at the same position in the extended atmosphere. To test the pumping mechanisms it is therefore of interest to determine the spatial distribution of the masers in each of these lines. To this end, we performed simultaneous observations of these two lines using the VLBA a few years ago. The results of our previous experiments (Jiyune Yi et al. 2000) led us to believe that a single epoch observation may not be able to give reliable answers on the pumping mechanism because of signs of stellar phase dependent properties.

We report our multi-epoch, simultaneous observations of $v\ =1$ and $v\ =2$ $J=1\rightarrow 0$ SiO masers in TX Cam using the VLBA. We present results from three epochs of maps in the two lines and discuss the spatial distribution of masing components over different stellar phases with the resolution of sub-mas. We examine the phase dependent characteristics of these masers, such as, variations of the maser ring size and the disruption of the maser ring shape, which are predicted by Gray and Humphreys (2000).

2. Observation and Data Analysis

We observed the 7 mm $v\ =1$ and $v\ =2$ SiO maser lines simultaneously toward TX Cam, using the VLBA. Three epochs of observations were made in 2000 May and September, and 2001 January; the corresponding stellar phases at these epochs are $\phi=\sim 0.64$, ~ 0.85, ~ 0.07 respectively. The data were recorded in right circular polarization with 8 MHz bandwidth and line rest frequencies of 43.122027 GHz for $v=1$ and 42.820542 GHz for $v=2$ were adopted. To track the delay across the two lines, we placed 2 of 8 bands centered at the $v\ =2$ and $v\ =1$ $J=1\rightarrow 0$ frequencies and the other 6 bands were spread evenly across the 300 MHz between the two lines. The synthesized beam was less than 0.4 mas × 0.2 mas.

3. Results

Due to the limited space for this paper, we present maps of both lines in one epoch which were observed in January 2001. But we describe results from all observations of three epochs in the following sub-sections.

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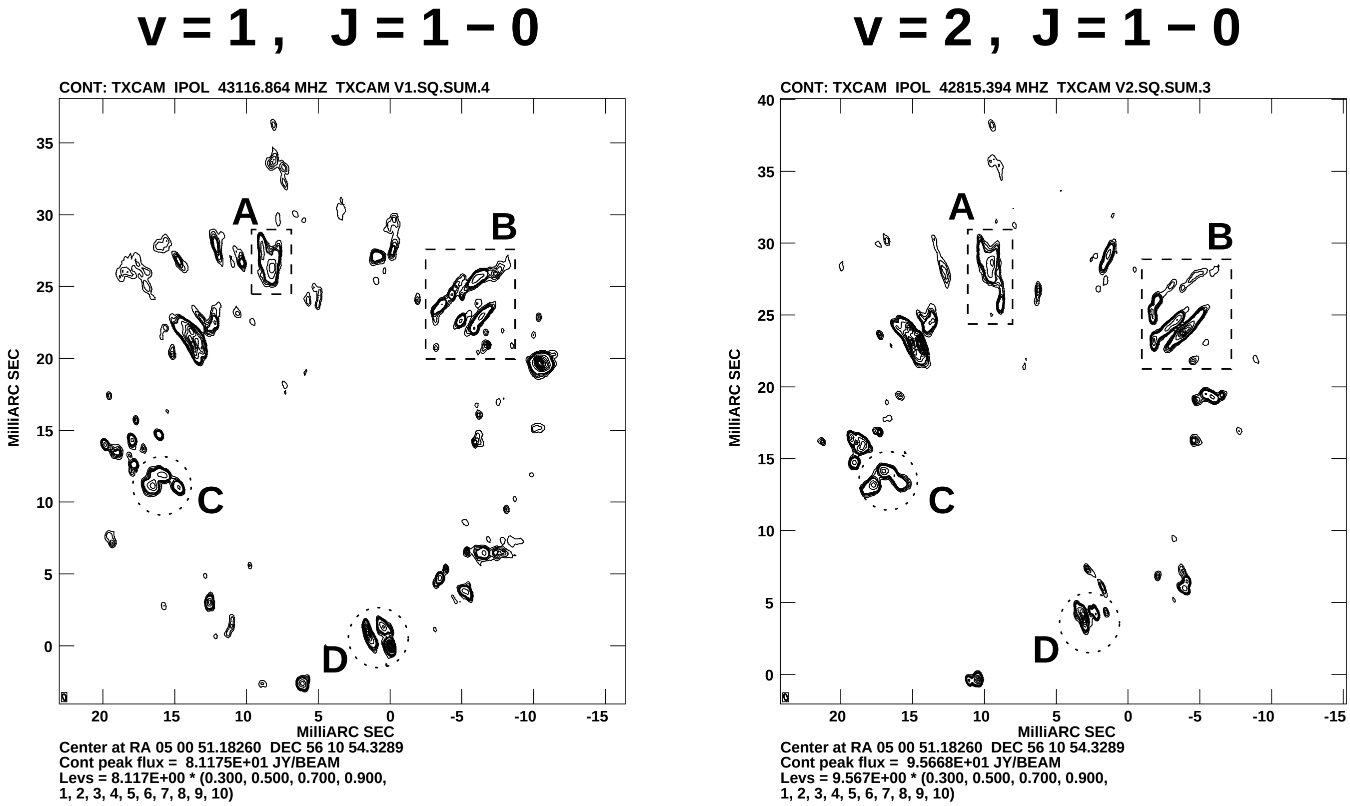

Fig. 1. The VLBI maps of the $v = 1$ $J = 1 \rightarrow 0$ (left) and $v = 2$ $J = 1 \rightarrow 0$ (right) SiO maser emission toward TX Cam observed in 2001 January.

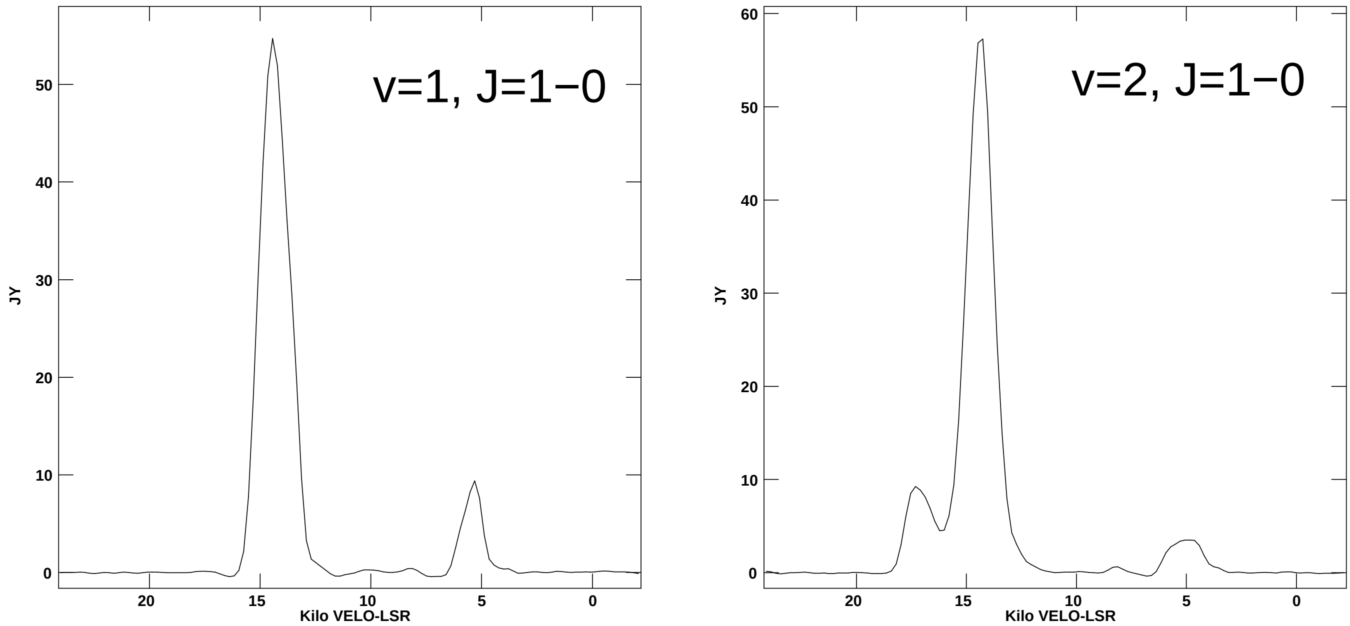

Fig. 2. The spectra of the emissions in the $v = 1$ (left) and $v = 2$ (right) $J = 1 \rightarrow 0$ lines in the region A.

3.1. Images from the observations in 2001 January

The optical phase at this epoch is $\phi \sim 0.07$. Figure 1 shows SiO maser maps of $v = 1$ (left) and $v = 2$ (right) $J = 1 \rightarrow 0$ integrated over all velocity channels containing emission. A full ring shape distribution of maser clumps is found in both maps; maser emissions range from ~ 1.7 to ~ 19 km s^{-1} in the $v = 1$ and ~ 2 to ~ 20 km s^{-1} in the $v = 2$ $J = 1 \rightarrow 0$ lines. There are many masing clumps appearing in both lines and their velocity ranges correspond to each other. Figure 2 presents the spectra of

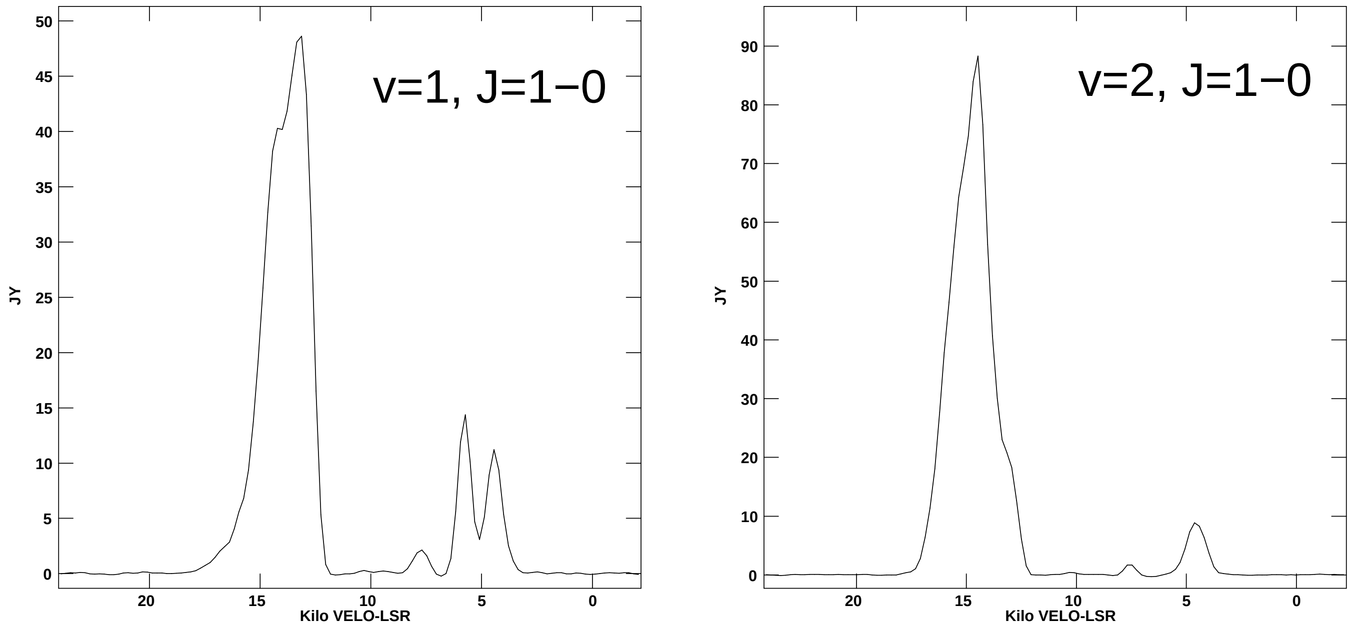

Fig. 3. The spectra of the emissions in the $v = 1$ (left) and $v = 2$ (right) $J = 1 \rightarrow 0$ lines in the region B

both lines from the masing clumps in the region marked as A in Figure 1. There are two distinctive velocity groups which appear in the spectra of both lines. The blue shifted (assuming the stellar velocity of ~ 9 km s^{-1}) components in both lines are much weaker and found to be mixed in the main features, whose velocity ranges from ~ 12 to ~ 16 km s^{-1} in the $v = 1$, and from ~ 12 to ~ 18 km s^{-1} in the $v = 2$ line. The masing feature which is tailing inward in the $v = 2$ $J = 1 \rightarrow 0$ line occurs in the clump with th e velocity from 16 to 18 km s^{-1}.

It is quite interesting to see spike-like masing clumps on the north-west side (marked B in Figure 1) in the maps of both lines; Figure 3 shows their spectra. The red-shifted components from ~ 12 to ~ 18 km s^{-1} in both lines occur from the spoke-like clumps and the blue-shifted components arise as small spot-like components in the region B in both maps. There are more blue-shifted emission spots in the $v = 1$ $J = 1 \rightarrow 0$ maser than in the $v = 2$ $J = 1 \rightarrow 0$ maser.

The largest size of maser rings in both lines was observed at the epoch of $\phi \sim 0.07$ in January 2001 among our observations of three epochs.

There are three clumps (marked A, B, & D in Figure 1) showing partial displacement with a linear size of about 1 to 2 mas between $v = 1$ and $v = 2$ $J = 1 \rightarrow 0$ line emissions. However, other common clumps observed in both lines show spatial coincidence. We will explore its implication further in the following discussion.

3.2. Images from the observations in 2000 September

The optical phase at this epoch is $\phi \sim 0.85$. A ring-like maser distribution is also seen at this epoch. However, emission is weaker and the numbers of masing clumps are fewer comparing to those observed in 2001 January. Some strong maser complexes which were seen in 2001 January have not yet developed at this epoch. The prominent spokes (in the region B in Figure 1) and maser complexes (marked C & D in Figure 1) in maps of both lines in January 2001 are good examples of newly developed masing clumps in four months. The diameter of the maser ring size is approximately 4 mas smaller than the one observed in four months later.

3.3. Images from the observations in 2000 May

The optical phase of TX Cam at this epoch is $\phi \sim 0.64$. Masers are not developed well at this epoch and due to fewer and weaker masing clumps, the maser rings shown in the later two epochs are not so clear at this epoch. It is known from many single antenna observations that optical, infrared, and millimeter SiO maser fluxes are correlated and there is an average phase lag of ~ 0.2 of a period between optical and maser maximum with some variations over different objects or cycles. Considering this phase lag we believe that SiO masers are near by the minimum at this optical stellar phase of $\phi \sim 0.64$.

3.4. Discussion

We have observed that the SiO masers in TX Cam have evolved over three epochs, separated by 0.2 of the stellar period. We show that our SiO observations can be explained well by the prediction of phase dependent properties (Gray & Humphreys 2000, Humphreys et al. 2002)

I. Among the three epochs, SiO masers are in 2000 May at the minimum of its optical phase of $\phi \sim 0.64$ and the ring-like distribution of masers is not apparently seen at this epoch. In our previous observations of TX Cam in '98 (Jiyune Yi et al. 2002) at the optical stellar phase of $\sim$ 0.54, we had also seen non-spherical maser distribution in both lines. Therefore, we confirm the prediction of maser ring disruption at the maser minimum phase.

II. The ring size become larger from 2000 May to 2001 January. We found that the maser ring radii are $\sim$ 2 mas larger in the maps of both lines observed in January 2001.

III. At the two stellar phases of $\phi \sim 0.85$ (September 2000) and $\phi \sim 0.07$ (January 2001), there is a significant overlap among the features in the $v = 1$ and $v = 2$ maps. Nevertheless, there is generally a small net inward displacement of the $v = 2$ ring. This is greatest at the epoch of $\phi \sim 0.07$ when the displacement is $1 \sim 2$ mas. It is difficult to quantify any displacement at the maser minimum ($\phi \sim 0.64$) since the rings are severely disrupted. The model (Humphreys, private communication) estimates the separation of maser rings between the $v = 1$ and $v = 2$ masers less than 1 mas in TX Cam (at the distance of 380 pc) when the maser flux becomes strong. Considering uncertainties of the distance to TX Cam and the model itself, we cannot provide exact linear quantities in terms of the variation of the maser ring separation between the two lines depending on stellar phases. However, we can state that we found the maser ring separation is mostly seen when the maser emission is strong, i.e. at the optical stellar phase of $\phi \sim 0.07$.

In our multi-epoch observations, we also observed another Mira variable, R Cas, whose distance is only 106.7 pc and measured by Hipparcos. We expect to see a solid evidence of the ring separation and its phase dependence in the two lines in R Cas. Data analysis is on the way.

4. Conclusions

We have conducted three epoch observations of $v = 1$ and $v = 2$ 43 GHz SiO maser simultaneously using the VLBA. We could track the delay over 300 MHz between the two lines and image maps of both lines successfully using all same calibration tables, given a relative positional accuracy of better than 1 mas.

We have shown phase dependent properties of SiO masers such as disruption of ring type distribution of masers at the maser minimum, variation of maser ring radii, and separations of maser rings between the two masers. The spatial coincidence of the two masers observed in a single epoch observation cannot be simply used in favor on one pumping model against another due to the maser phase dependence. Depending on the distance of the observed star or stellar phases, it may become difficult to determine the ring separation even with the VLBA resolution. Although we have confirmed maser phase dependent properties in general, there could be some discrepancies in details, such as the size of ring separation differing by different Mira variables or different stellar phases. We believe our observations are well explained by models (Gray & Humphreys 2000, Humphreys et al. 2002) in general but examination in detail and more discussion on the implications of our observational results are needed to be made further in the future.

References

Gray, M. D., & Humphreys, E. M. L., 2000, New Astronomy, 5, 155

Humphreys, E. M. L., Gray, M. D., Yates, J. A., Field, D., Bowen, G. H., & Diamond, P. J. 2002, A&A, 386, 256

Jiyune Yi, Booth, R.S., Conway, J.E., Diamond, P. J., & Winnberg, A., 2000, in Proceedings of the 5th European VLBI Network Symposium, ed. J. E. Conway et al.

Jiyune Yi, Booth, R.S., Conway, J.E., Winnberg, A., & Diamond, P. J., 2002, in IAU Symp 206, 266 Cosmic MASERs: From Protostars to Blackholes, ed. V. Migenes