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VLBA observations of the 7mm SiO masers in TX Cam and R Cas

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Abstract. Simultaneous VLBI observations of the SiO masers of the $J = 1 \rightarrow 0$ rotational line in the v = 1 and v = 2 vibrational levels toward Mira variables are presented. Because SiO maser lines are formed deep in circumstellar envelopes they serve as a unique tool to study the innermost envelopes of evolved stars. Although the first interpretation of SiO maser emission was made in 1974, observational features are only partially explained by models which have been suggested since then. Positional coincidence of the $J = 1 \rightarrow 0$ masers of v = 1 and v = 2 has been argued as a way to distinguish among the maser pumping models, but it requires simultaneous observations of the two lines using high resolution. We have developed the technique for such observations during the last few years and here we report successful results of our simultaneous observations of the SiO v = 1 and v = 2 $J = 1 \rightarrow 0$ masers using the Very Long Baseline Array (VLBA). We discuss the pumping mechanism in terms of our observational results.

1. Introduction

Many circumstellar envelopes of evolved stars host OH, H_2O, and SiO masers. The conditions required for the formation of these circumstellar masers place them in a hierarchical distribution from the central star. SiO masers occur from rotational transitions within excited vibrational states, which need higher excitation energy (~1800 K for the first vibrational state) than those required for OH or H_2O masers in the ground vibrational states. SiO is depleted in the gas phase once dust grains form because of its incorporation into grain particles. Therefore, SiO masers can serve as a unique probe of the region close to the stellar photosphere, inside the dust forming layer. However, these extended atmospheres suffer from stellar pulsations and shocks which complicates the underlying physics of the pumping mechanism.

Comparisons of single-dish line profiles are most often used to understand physical properties of the masing regions. However, due to the variability of the SiO maser emission, it is important to make simultaneous observations of the various lines to infer reliable conclusions about the excitation conditions of the masers. High resolution interferometric observations of circumstellar masers provide valuable information. VLBI mapping of SiO masers enables direct study of the extended atmosphere; they are found within a few stellar radii of the photosphere and show a complex structure down to sub-milliarcsecond (mas) scales in the v = 1 , $J = 1 \rightarrow 0$ transition.

Although the first interpretation of SiO maser emission appeared in 1974 (Kwan & Scoville), debate on the pumping mechanisms continues. 7mm observations of SiO masers in the v = 1 and v = 2 , $J = 1 \rightarrow 0$ can be useful in this regard. A standard radiative pumping 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. The first simultaneous observations of two SiO maser lines at 7mm using a single baseline were reported by Miyoshi et al. (1994). They measured spatial coincidence between the maser spots in the v = 1 and v = 2 , $J = 1 \rightarrow 0$ to within 7 mas and from their result, argued in favour of collisional pumping.

We have conducted simultaneous observations of these two lines in the Mira variables, TX Cam and R Cas using the VLBA in the hope that we can discern the spatial distribution of masers in the v = 1 and v = 2 transitions, and compare them with earlier unpublished observations by Booth et al. from 1995 (see Yi et al. 2000).

2. Observations

Simultaneous observations of two 43 GHz SiO maser lines in the $v = 1$ and $v = 2$, $J = 1 - 0$ toward TX Cam and R Cas were made using the Very Long Baseline Array (VLBA). Each source was observed for 4 hours in September 1998. The data were recorded in right circular polarization with a 8 MHz bandwidth ($\sim$ 56 $km\ s^{-1}$); line rest frquencies of 43.122027 GHz for $v = 1$ and 42.820542 GHz for $v = 2$ were adopted. The synthesized beam was $\sim 0.6 \times 0.4$ milliarcsec for TX Cam and $\sim 0.5 \times 0.4$ mas for R Cas. Calibration and image processing are quite challenging tasks for the simultaneous of observations of two lines and we will describe them in more detail in a forthcoming paper.

3. Results

3.1. TX Cam

Maser features appear in the velocity ranges between 3.4 $\mathrm{km\,s^{-1}}$ and 14.6 $\mathrm{km\,s^{-1}}$ in the $v = 1$ line, and 3.1 $\mathrm{km\,s^{-1}}$ and 15.3 $\mathrm{km\,s^{-1}}$ s in the $v = 2$ line respectively. The optical phase of TX Cam at this epoch was $\phi \sim 0.54$. Figure 1 shows images integrated over all velocity channels containing emission from two epochs of observations toward TX Cam. The ring structure observed by Booth et al. in 1995 ($\phi \sim 0.21$) were closely similar in the two lines with similar velocity features corresponding to each other (Fig. 1, upper). In the images of our new observations (Fig. 1, lower) in '98 the maser shells appear to be disrupted and the v=1 masers are, in general, further from the star than the v=2 features.

Most of the features on the western side, which are blueshifted (assuming a stellar velocity of 9 $\mathrm{km\,s^{-1}}$) and shown by other obervations (see Diamond, this volume), have disappeared in the later epoch but two blueshifted maser complexes appear persistently on the south-west side over both observations. All redshifted maser spots lie on the eastern side. These velocity distributions

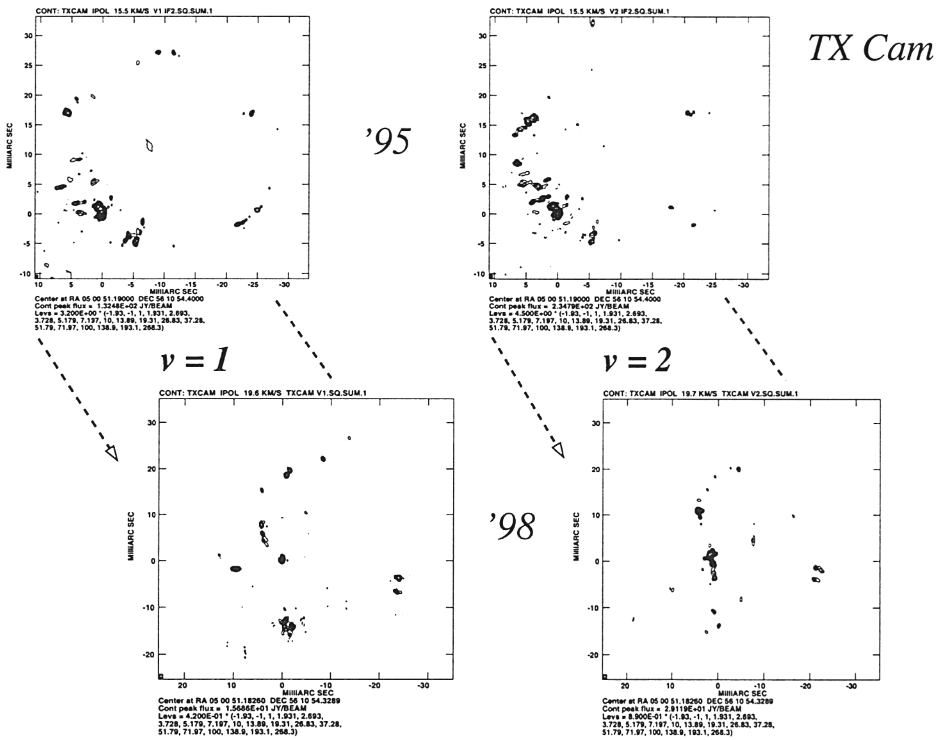

Figure 1. Images of $v = 1$ (left) and $v = 2$ (right) at 43 GHz SiO masers from the observations of '95 (upper) and '98 (lower).

are consistent with the v = 1 line results of Diamond & Kemball (1999) and with the hypothesis of tangential amplification of the masers.

3.2. R Cas

Maser emission lies in the velocity ranges 19.8 to 35.6 $\mathrm{km\,s^{-1}}$ in the v = 1 line and 20.2 to 35.7 $\mathrm{km\,s^{-1}}$ in the v = 2 line. The optical phase at this epoch was $\phi \sim 0.27$. Although both maser lines exhibit a basic circular symmetry, the rings display abundant spokes (radial extensions) on the south-west quadrant with complex velocity distributions around the stellar velocity (25 $\mathrm{km\,s^{-1}}$). There are only a couple of maser spots on the north-east quadrant. The existence of the 'spokes' makes it difficult to define a single value of diameter. However, we estimate the inner ring to have a diameter of ~ 41 mas in the v=1 line and ~ 38 mas in the v=2 line. Complex structure was also seen in observations by Booth et al. in 1995, but these observers were concerned that it might be instrumental

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in origin. The new observations confirm their reality. A full description of R Cas in both lines together with images and discussion will be presented in a forthcoming paper.

4. Discussion

Our VLBA data confirm the ring-like structure of 43 GHz SiO masers in both vibrational states of the J=1-0 transition. TX Cam shows similar diameter rings at the stellar phase of $\phi \sim 0.21$ but later in the stellar cycle ($\phi \sim 0.54$) the rings are disrupted and the v=1 and v= 2 mases are at different distances from the star. Such behaivour has been predicted by the simulations of Humphreys et al. (1996) who show that in general, $v = 2$ masers lie a little inside (closer to the star) than the equivalent $v = 1$ masers. A model by Gray & Humphreys (2000) predicts that, at each epoch of the stellar phase, the ring of brightest v = 1 and v = 2 masers will be separated by a phase-dependent distance of $0.1 \sim 0.3$ AU. This phase-dependence of maser ring radii between these two lines is explained by a shock traversing the maser zone which excites the v = 2 , 43 GHz maser first, also causing v = 2 maser ring to expand before the v = 1 ring. Using the Hipparcos distance to R Cas (106.7 pc) we find a $v = 1, 2$ ring separation of 0.16 AU.

A discussion of maser pumping from the comparison of spatial distributions between $v = 1$ and $v = 2$, 43 GHz masers at a single epoch would be premature. We have performed multi-epoch VLBA observations to confirm the phase dependence features and constrain inversion scheme with higher plausibility. In the forthcoming paper(s) we will be able to present multi-epoch images of both TX Cam and R Cas at different stellar phases and, we hope, ever-firmer constraints on pumping models.

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