# Simulating VLBI Observations of Circumstellar SiO Masers

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We have coupled a hydrodynamic model of a pulsating Asymptotic Giant Branch (AGB) star to a SiO maser model in order to calculate the morphology and intensity of circumstellar SiO maser emission as a function of the stellar pulsation cycle.

## 1. Introduction

It is well-known from VLBI experiments that bright $v = 1$, $J = 1 - 0$ SiO maser components in M-Mira and Supergiant stars lie in approximate ring-type morphologies of several AU in diameter (in the range 1.5 – 4.0 $R_*$), which are assumed to be centered on the stellar position (see e.g. Diamond et al. 1994). The projected ring of clumpy emission is observed to contract and expand, brighten and dim, with stellar phase during the pulsation cycles of M-Mira stars such as TX Cam and R Aqr (Diamond et al. 1994; Boboltz et al. 1997). M-Miras and other classes of stars on the thermally-pulsing AGB are of interest due to their high mass loss rates (in the range $10^{-7}$ – $10^{-4}$ $M_{\odot}yr^{-1}$) which replenish the interstellar medium with heavy elements and dust grains. SiO masers, which may now be studied at 43-GHz with a spatial resolution of 200$\mu$as and a velocity resolution of 0.1 $kms^{-1}$ using VLBI, provide excellent probes of the dynamics and time-varying physical conditions of the inner circumstellar envelopes (CSEs) of AGB stars.

In the present work, we combine a model of a pulsating M-Mira star, in which mass loss is driven by shocks and radiation pressure on dust, with a SiO maser model. Humphreys et al. (1996; H96) showed how, at a single stellar phase, the key features of SiO maser emission are reproduced by such a model. The aim of the present study is to model the morphology and intensity of circumstellar SiO maser emission as a function of stellar pulsation phase. This constitutes a more rigorous test of whether a stellar model which drives mass loss through shocks and radiation pressure on dust yields maser emission features which are consistent with those observed.

## 2. VLBI Observations

The observed features which a circumstellar SiO maser model should reproduce include:

1. At VLBA resolution, SiO masers form in unfilled ring-type structures of several AU in diameter (in the approximate range 1.5 – 4.0 $R_*$) assumed to be centered on the stellar position, indicative of a tangential maser beaming. The diameter of the ring is dependent on the star and on the stellar pulsation phase.

2. VLBI observations show evidence for complex structural changes in maser morphology during the stellar cycle. Emission from both infalling and outflowing material is observed. Towards R Aqr, the average infall proper motion for $v = 1$, $J = 1-0$ (43-GHz) components was measured to be 1 mas in 98 days (corresponding to 0.22 AU for R Aqr at a distance of 220 pc) (Boboltz et al. 1997).

3. Simultaneous observations of $v = 1$ and $v = 2$ $J = 1 - 0$ masers at 43-GHz indicate rings of emission are spatially separated, at least at some epochs. The average difference in ring radii between the transitions has been measured to be 1.5 mas for R Cas (0.16 AU at 107 pc; Yi et al. 2000) and 1.3 mas for TX Cam (0.41 AU at 317 pc; Desmurs et al. 2000).

4. Intensity of maser emission varies during the stellar cycle. Disruption of the maser emission ring occurs around maser minimum light (Yi et al. 2000). A new ring of emission is observed to appear at minimum maser light, at an optical phase of 0.67, at the inner radius of the previous ring (Diamond, private communication).

We note also that the SiO maser emission from AGB stars is often strongly linearly polarized with weaker circular polarization, a feature not treated by our model. See Kemball & Diamond (1997) for more details.

## 3. Modelling method

The calculation of SiO maser spectra and images is performed at 20 epochs (every 16.6 days $\equiv$ 0.05 stellar periods) during one pulsation cycle of the model M-Mira star. For details of the stellar hydrodynamic pulsation code see Bowen (1988) and H96. The SiO maser model is a 1-D, semi-classical radiation transport code based on that of Doel et al. (1995). It involves the calculation of the populations of 200 rovibrational energy levels for SiO using the Large Velocity Gradient approximation. The propagation of maser radiation is calculated including the effects of maser saturation and a velocity gradient in the direction of maser propagation. We describe how these models are coupled below.

VLBI maps of SiO 43-GHz emission clearly show that, at a particular range of radial distances from the photosphere, only certain regions of gas in the CSE are capable of sustaining maser action. In order to break the spherical symmetry of our CSE model, we therefore choose sites of potential maser action in the CSE on a random basis at the first epoch of our calculations. SiO maser emission is possible from these sites, and not at other sites at the same radius in the model, as they are assumed to be abundant in SiO ($n(SiO) : n(H_2) = 10^{-4}$). Assuming that maser zones maintain their integrity throughout the stellar cycle, the trajectories of these initially chosen sites are then followed in terms of their radial distances from the star as the cycle progresses, using velocity data from the stellar pulsation model.

At any chosen epoch, for each radial distance, a gas number density ($n(H_2)$), kinetic temperature and velocity field may be assigned from the stellar model. For each site, SiO rovibrational level populations may therefore be calculated. If these populations lead to inversions, the intensities of the resulting masers are calculated for paths in our line-of-sight, as described in H96. In this way, images of SiO maser emission are calculated for as many epochs of the stellar cycle as required and for any masing transition. For any given transition, maser spectra at each epoch are generated by summing over the intensity contributions of individual maser spots, with line-of-sight velocity shifts appropriate for their position. Synthetic maser images are produced by plotting the velocity-integrated intensity of each component at the projected position of the site.

## 4. Results & Conclusions

We compare the results of our calculations (see Figures 1 & 2) with the observed features of circumstellar SiO masers listed in Section 2.

1. Figure 1 shows that bright $v = 1$, $J = 1 - 0$ SiO maser emission forms in a ring-type

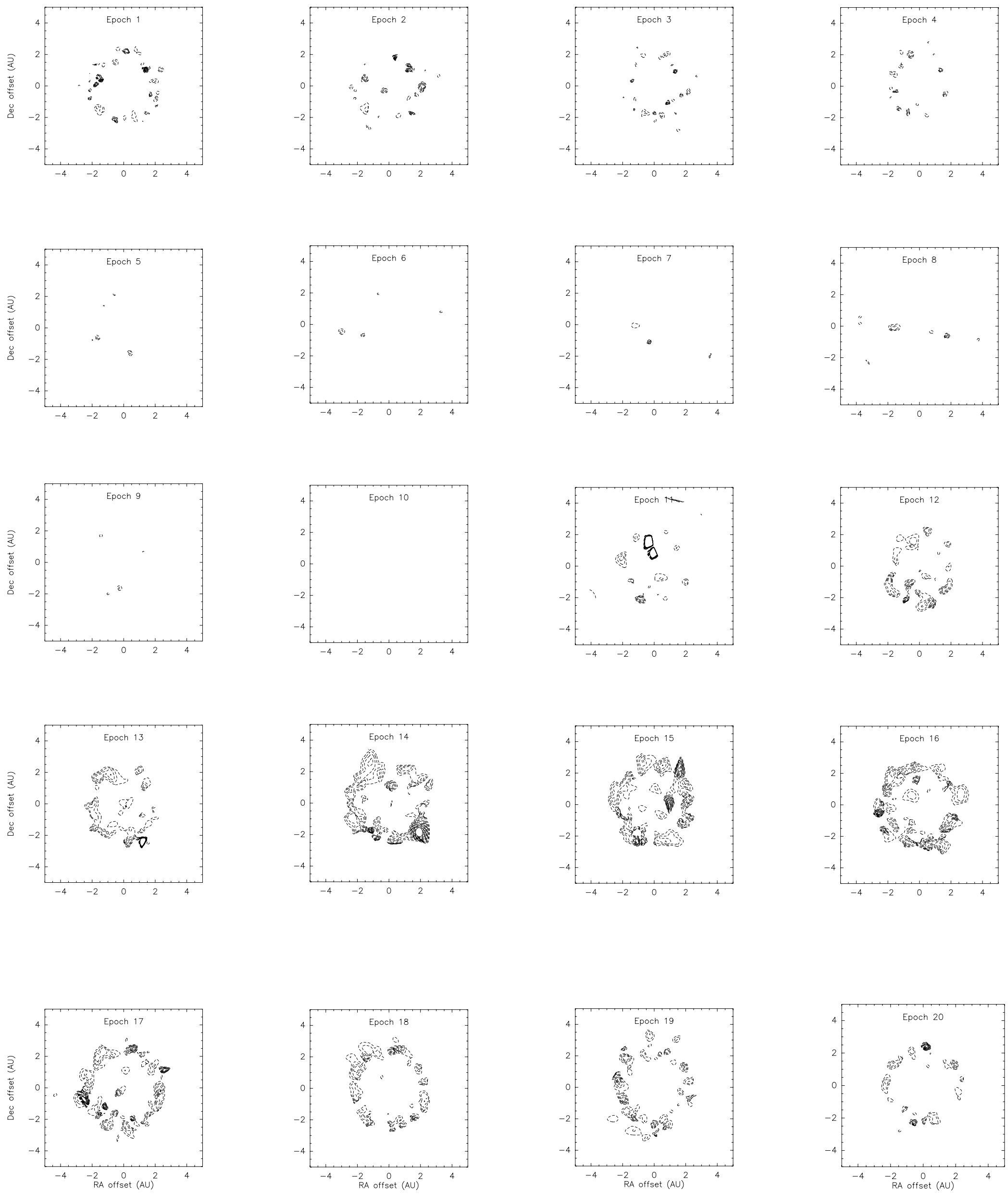


FIGURE 1. Calculated images of $v = 1$ 43-GHz masers at twenty epochs (every 16.6 days). The 'out-of-page' axis is the log of the velocity-integrated intensity, $I_{VEL}$. The contour levels are regularly spaced from log $I_{VEL}$ = -13.0 to 0.0, in order to indicate the broad range of peak values of log $I_{VEL}$ between epochs. $1R_* \equiv 1.1$ AU; 1 stellar period = 332.0 days.

structure of diameter in the range 3.9 – 4.6 AU. The ring radius differs by stellar phase, as observed. Figure 2 shows how a small initial contraction of the maser ring occurs, followed by a larger shock-driven expansion. At high epochs, the expansion is halted by gravity, and a slow contraction begins.

2. Ring radii also differ by transition. Figure 2 shows that the maser zones for the

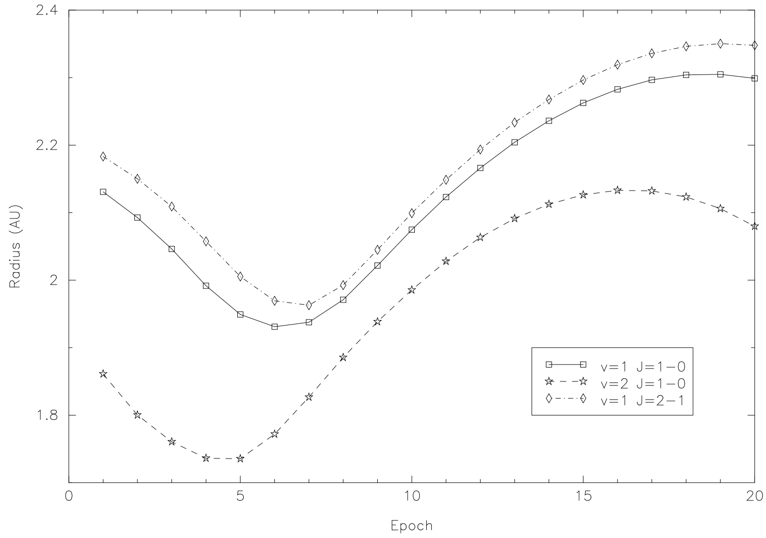


FIGURE 2. The mean radius of the fifty brightest maser features, generated by the model Mira variable, as a function of stellar phase. For more details see Gray & Humphreys 2000.

$v = 1$ $J = 1 - 0$ and $J = 2 - 1$ (86-GHz) lines are closely coupled, with a ring of similar size, but the ring of $v = 2$ $J = 1 - 0$ masers lies significantly inside the others at all epochs. The separation of the two 43-GHz maser rings in the model is 0.1 − 0.3 AU as a function of stellar phase, in good agreement with the results of Yi et al. (2000).

3. There is a net outflowing proper motion of maser components during the stellar cycle. However bright $v = 1$ 43-GHz maser components infall on average by 0.2 AU in 83 days, in close agreement with the measurements of Boboltz et al. (1997).

4. Intensity of maser emission varies during the cycle. Disruption of emission occurs at minimum maser light as observed, when a high temperature shock front passes through the maser zone. Bright maser emission forms in the wake of the shock wave, in regions of enhanced temperature and gas density.

We conclude that coupling a SiO maser model to a M-Mira model, in which the mass loss process is driven through a combination of stellar pulsation-driven shock waves and radiation pressure on dust, performs well in reproducing the observed features of circumstellar SiO masers.

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