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Exploring the short timescale variability of SiO masers in evolved stars

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Abstract

Asymptotic Giant Branch stars (AGBs) are evolved intermediate-mass objects characterized by strong stellar pulsations and a copious mass loss that leads to the formation of a circumstellar envelope. The formation of SiO maser emission takes place in the innermost layers of these circumstellar envelopes, being a useful tool for studying those regions. AGBs show strong flux variations at all wavelengths, including the SiO maser lines. The periods of these variations are 300–500 days in regularly variable (Mira-type) stars and slightly smaller in semi-regular and irregular variables. Using the Yebes-40m radio telescope, we are monitoring several SiO lines at 7 mm in 24 sources, to study the long-term variability in these objects. Our sample includes sources of different natures, such as AGBs, post-AGBs, supergiant stars, and symbiotic systems. Furthermore, we studied the variability of the SiO maser lines at 3 and 7 mm in short-time scales ($\sim$few days) via observations with the IRAM-30m and the Yebes-40m radio telescopes. The variations in the intensity of the SiO lines found towards the observed Mira-type variables agreed with their long-term variability curve showing changes about 10 % in 7-10 days. However, surprising results were found in the semi-regular variable RX Boo, whose SiO maser lines changed in intensity by about 50 % in two-three days. Currently, we are studying the variability of the SiO lines at 7 mm in the different types of semi-regular variables (SRa, SRb, and SRc) using single-dish observations with the Yebes-40m. Our preliminary results show that the variability of these lines in SRb variables is similar to RX Boo, suggesting that the properties of the SiO-emitting spots are similar in these objects and different from other type of variables, Miras, SRa, or SRc.

1 Introduction

During the asymptotic giant branch (AGB) phase, strong pulsations and mass loss take place, and a circumstellar envelope (CE) is formed around the star as a result. The properties of the inner part of the CE, a particularly important region to understand the mass-loss process, can be studied using SiO maser lines (e.g., Habing 1996). SiO maser emission takes place between rotational levels (J = 1–0, 2–1, 3–2, ...) in excited vibrational states (v = 1, 2, 3, and 4). The most intense maser lines are v = 1,2 J = 1–0 and v = 1 J = 2–1, with the v = 2 J = 2–1 line usually not detected. The rotational lines in the vibrational state v = 0 are often much weaker than the $v > 0$ maser lines but also present maser emission, particularly in the ^{29}SiO and ^{30}SiO isotopes. ^{28}SiO $v = 0$ lines often show relatively weak maser features (Boboltz & Claussen 2004; de Vicente et al. 2016), with the bulk of the profile being due to thermal emission. Very long baseline interferometry (VLBI) studies show that SiO masers come from many compact spots (a few milliarcseconds wide), which form ring-like structures at typical distances of a few stellar radii (see Diamond et al. 1994; Soria-Ruiz et al. 2004).

Stars on the AGB are long-period variables that present strong flux variations at optical, infrared, and radio wavelengths, including the SiO maser lines. The periods of these variations are of 300–500 days in Mira-type stars, which are relatively regular variables. Typically, SiO masers show significant variations (∼20%) over 1-3 months. On the contrary, the variability of the v = 0 lines is negligible; at least for the thermal component. Semi-regular and irregular variables are characterized by a less well-defined period and smaller amplitudes (Habing 1996). In regular variables, the SiO maser variability follows the infrared curve, with a phase lag of 0.1–0.2 with respect to the optical curve. This behavior strongly suggests that the maser pumping is mainly radiative through the absorption of stellar 8 µm photons (e.g., Pardo et al. 2004; Soria-Ruiz et al. 2004). However, other pumping mechanisms have been proposed to explain the observed properties of SiO maser in AGB stars, such as for example in the collisional models (e.g., Locket & Elitzur 1992). Semi-regular variables present a strong and erratic variability in the maser line intensity on timescales of several months. At the minimum of their variability curves, SiO lines are weak and sometimes not detected for months in semi-regular variables. Previous studies of variable stars only included a few semi-regular variables, such as for example RT Vir in Alcolea et al. (1999) and Pardo et al. (2004). Kim et al. (2018) also performed VLBI observations at 7 mm of the semi-regular R Crt in three epochs. In general, the SiO emission from semi-regular variables was found to be weak and erratic. Some indications of the presence of rapid variations were reported in these previous studies, but they were not tight and systematic enough to characterize fast variability in semi-regular variables

2 Observations

Several evolved stars were studied in this work including the prototypical Mira-type stars U Her, R Leo, and R LMi, the semi-regular variables RX Boo, RT Vir, R Crt, V370 And, GY Aql, VX Sgr, VY CMa and W Hya, and the S-type Mira variable χ Cyg. We explored the variability, in short timescales, of the SiO maser lines at several frequencies covering various

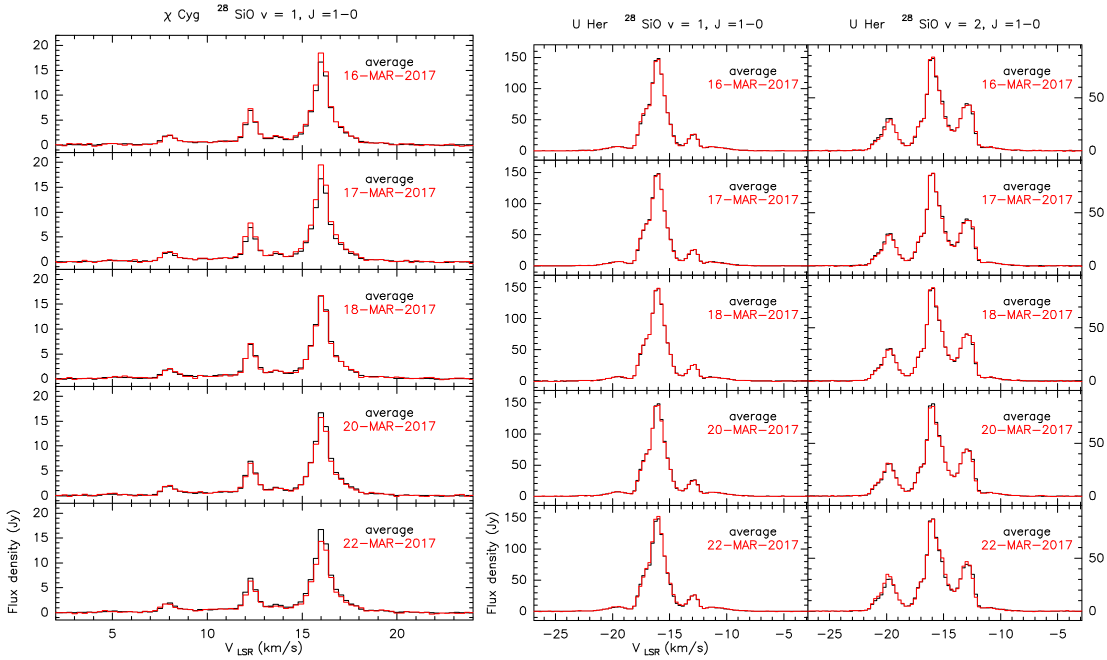

Figure 1: *Left.* Time evolution of the SiO v=1 J=1–0 lines observed in *chi* Cyg during our March 2017 observing run. *Right.* Time evolution of the SiO v=1,2 J=1–0 lines observed in U Her during our March 2017 observing run. In both cases, the average spectrum of the complete run is plotted in black and the individual (one per day) spectra are plotted in red.

rotational transitions, including J=1–0, 2–1, and 3–2. With this information we can explore the differences between the fast variability of SiO masers at different frequencies.

2.1 Single-dish observations

We carried out observations with a minimum spacing of one day, searching for fast variations in the intensity of the SiO maser lines. We observed the 7, 3, and 2 mm using the 40 m antenna at Yebes Observatory (Guadalajara, Spain) and the IRAM 30 m at Pico Veleta (Granada, Spain). These observational runs were performed in several epochs: August 2016, September 2016, March 2017, August–September 2017, November 2017, March 2020, and June 2020. The SiO maser lines at 7 mm were obtained using position-switching method while the SiO transitions at 2 and 3 mm were observed using the wobbler-switching procedure.

In order to improve the calibration, we observed thermal lines with high S/N when possible. The intensities of these lines, such as the SiO v=0 J=1–0, 2–1, and 3–2 transitions, are constant in time and significant changes their profiles are not expected in few weeks (Gómez-Garrido et al. 2020). Our observations required a total telescope time of ~1000 h.

2.2 VLBA

The SiO v=1,2 J=1–0 lines were observed with the VLBA antennas in two different epochs. Due to the low S/N of the SiO v=1 J=1–0 transition, only the maps of the SiO v=2 J=1–0 are presented here.

3 Results and analysis

Figs. 1, 2, and 3 show the time evolution of the SiO v=1,2 J=1–0 maser lines in χ Cyg, U Her, GY Aql, VX Sgr, RX Boo, and R Crt. These figures are a representative sample of the data obtained for the single-dish observations where we show observations of two Mira-type variables, U Her and χ Cyg, one SRa and SRc, GY Aql and VX Sgr, and two SRb, RX Boo and R Crt. Fig. 4 shows the VLBI maps for the SiO v=2 J=1–0 line observed towards RX Boo in two different epochs three days apart.

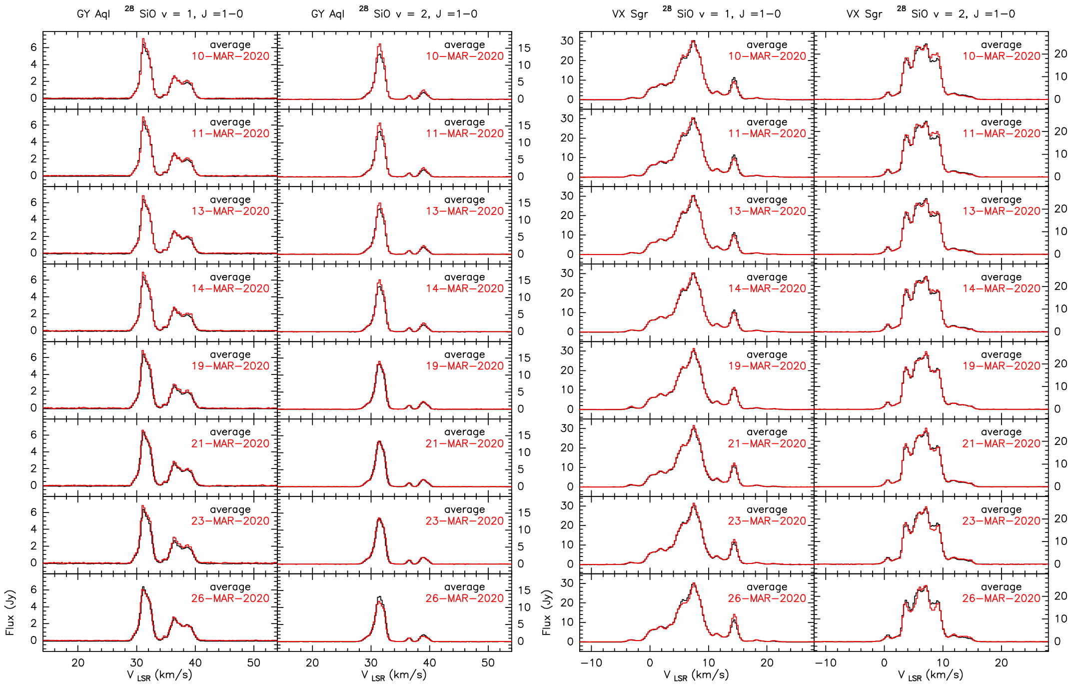

Figure 2: *Left.* Time evolution of the SiO v=1,2 J=1–0 lines observed in GY Aql during our March 2020 observing run. *Right.* Time evolution of the SiO v=1,2 J=1–0 lines observed in VX Sgr during our March 2020 observing run. In both cases, the average spectrum of the complete run is plotted in black and the individual (one per day) spectra are plotted in red.

The variability exhibited by GY Aql and U Her agrees with the expected behavior for the long-term changes in the intensity of the SiO maser (see Alcolea et al. 1999 and Pardo et al. 2004). Differences smaller than 10 % are found when the intensity of the same spikes are

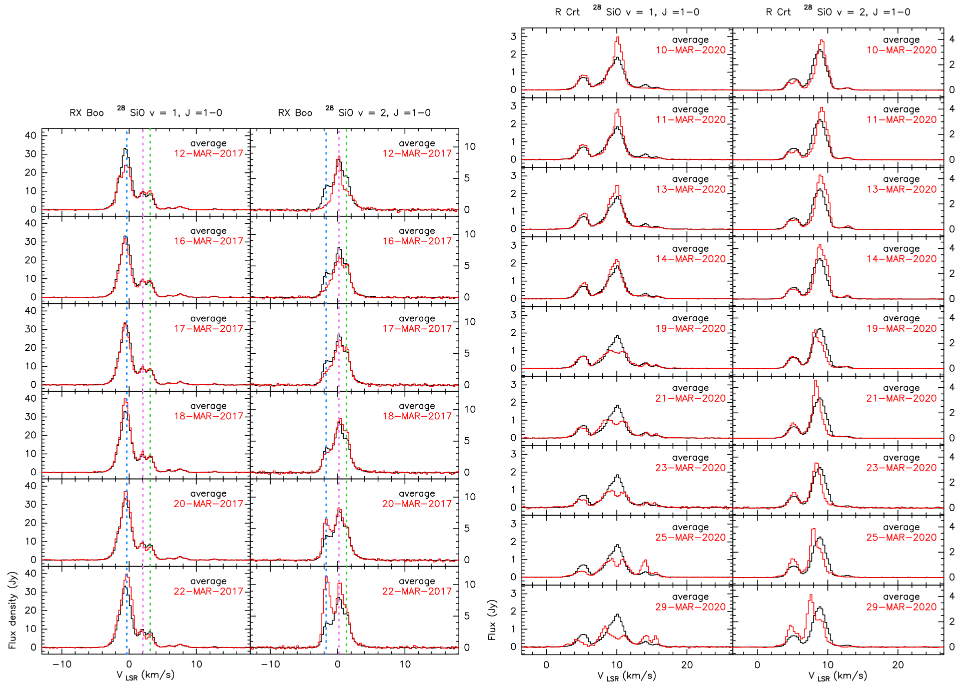

Figure 3: *Left.* Time evolution of the SiO v=1,2 J=1–0 lines observed in RX Boo during our March 2017 observing run. *Right.* Time evolution of the SiO v=1,2 J=1–0 lines observed in R Crt during our March 2020 observing run. In both cases, the average spectrum of the complete run is plotted in black and the individual (one per day) spectra are plotted in red.

compared in observations separated by ten days. Similar variability of the SiO maser lines has been found in the other Mira-type, SRa, and SRc variables observed.

Strong variability of the SiO maser lines are clearly detected in SRb variables RX Boo and R Crt. In particular, changes in the intensity of the spikes larger than 50 % are usually detected in observations separated by two or three days. This unexpected behavior has been observed in the other SRb variable in this project. From the variability curve of the SiO masers towards RX Boo, we estimate a period of eight days for these fast variations.

This fast variability of the SiO maser lines can be explained due to the smaller size of the emitting-spots. Using VLBI techniques, we mapped the SiO v=2 J=1–0 line in the SRb variable RX Boo and we found that the sizes of these structures are ~0.2 au (see Fig. 4). Even this value is smaller than those found in Mira-type variables (Yun et al. 2016 and Chen et al. 2006) faster shocks are required to explain the rapid intensity changes detected.

4 Conclusions

The variability of the SiO maser lines in short timescales observed towards the Mira-type, SRa, and SRc variables agrees the long-term variability curves and only changes ~5-10% in

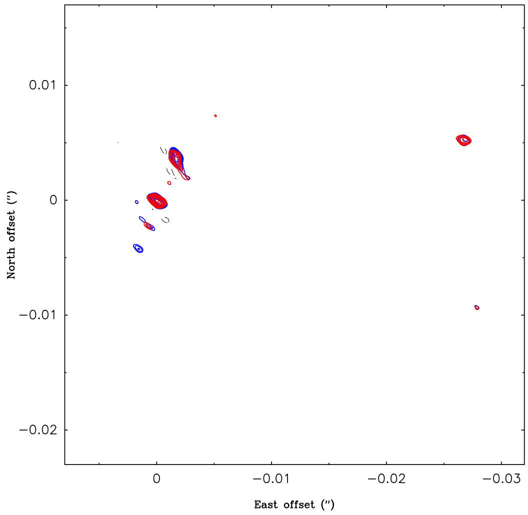

Figure 4: VLBA maps of the SiO v=2 J=1–0 line towards RX Boo. Blue and red contours show observations performed with a separation of three days.

the intensities of the lines are found. Strong changes in the intensities of the SiO lines are detected towards the SRb variables studied. They show variations larger than 50 % in 3 three days in many cases. This common behavior suggests a different structure sin the innermost regions of the SRb variables, or different evolutionary stage.

Acknowledgments

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