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First VLBA observations of ^{28}SiO J=1-0, v=3 maser emission from AGB stars

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The v=1 & v=2 J=1–0 (43 GHz), and v=1 J=2–1 (86 GHz) SiO masers are intense in AGB stars. They have been mapped using VLBI displaying spots ring-like distributions. The rings of the v=1, v=2 J=1-0 masers are similar, but the spots are rarely coincident, while the v=1 J=2–1 maser arises from a well separated region farther out. The v=3 J=1–0 line is not directly affected by any line overlap and its spot structure and position, relative to the other lines, is a good test to the standard pumping models. We present simultaneous single dish and VLBI observations of the v=1, v=2, and v=3 J=1–0 maser transitions of ^{28}SiO in several AGB stars and compare them to model predictions.

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1. Introduction

Many asymptotic giant branch (AGB) stars have been mapped in SiO maser emission in the J=1–0 v=1 and 2 lines, particularly using the NRAO[1] VLBA ([7], [5], [4], etc). The maser emission is found to form a ring of spots at a few stellar radii from the star center. In general, both distributions are similar, although the spots are very rarely coincident and the v=2 ring is slightly closer to the star than the v=1 ring. (see e.g. [5]).

The similar distributions of the v=1, 2 J=1–0 transitions were first interpreted as favoring collisional pumping, because the radiative mechanisms tend to discriminate more the location of the two masers. On the contrary, the lack of coincidence was used as an argument in favor of radiative pumping, leading to the well-known, long-lasting discrepancy in the interpretation of the v=1, 2 J=1–0 maps in terms of pumping mechanisms (see discussion in e.g. [5]).

The discussion on this topic dramatically changed when the first comparisons between the v=1 J=1–0 and J=2–1 maser distributions were performed (see [13], [14], [15]). In contradiction with predictions from both models (radiative and collisional), the v=1 J=2–1 maser spots systematically delineate a ring with a significantly larger radius (by 30%) than that of v=1 J=1–0, both spot distributions being completely unrelated. [13] interpreted these unexpected results invoking line overlap between the ro-vibrational transitions v=1 J=0 – v=2 J=1 of SiO and ν_2=0, $J_{k,k}$=$12_{7,5}$ – ν_2=1, $J_{k,k}$=$11_{6,6}$ of H_2O. According to [13], this phenomenon, first proposed by [12] to explain the weakness of the v=2 J=2-1 SiO maser, would also introduce a strong coupling of the v=1 and v=2 J=1–0 line, explaining their similar distribution.

If our present theoretical ideas are correct (e.g.[2], [3], [11], [8]), the v=3 J=1–0 emission requires completely different excitation conditions than the other less excited lines. No pair of overlapping lines is known to couple the v=3 J=1–0 inversion with any of the other SiO lines. The v=3 J=1–0 spatial distribution should in principle be different compared to the J=1–0 v=1, 2 ones and, of course, of the J=2–1 v=1 maser, and placed in a still inner ring.

2. Observations and Results

2.1 Onsala monitoring

The v=3 J=1–0 line is sometimes quite intense [1] and bright enough to be mapped with the VLBA, but is strongly variable, both in time (with characteristic time scales of a few months) and from object to object. We have been monitoring a list of 19 AGB stars using the 20-m antenna at Onsala at 43 GHz (see [6]), observing simultaneously the v=1, 2, 3 J=1–0 line in both right and left circular polarizations, with a spectral resolution of 25 kHz ($\sim$0.2 km.s^{-1}).

Several sources were dectected and four were selected to be mapped with the VLBA. In Figure 1 we show the single dish spectra in dates close to the VLBI observations of the four selected candidates: R Leo, IK Tau, TX Cam and U Her.

[1]The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc

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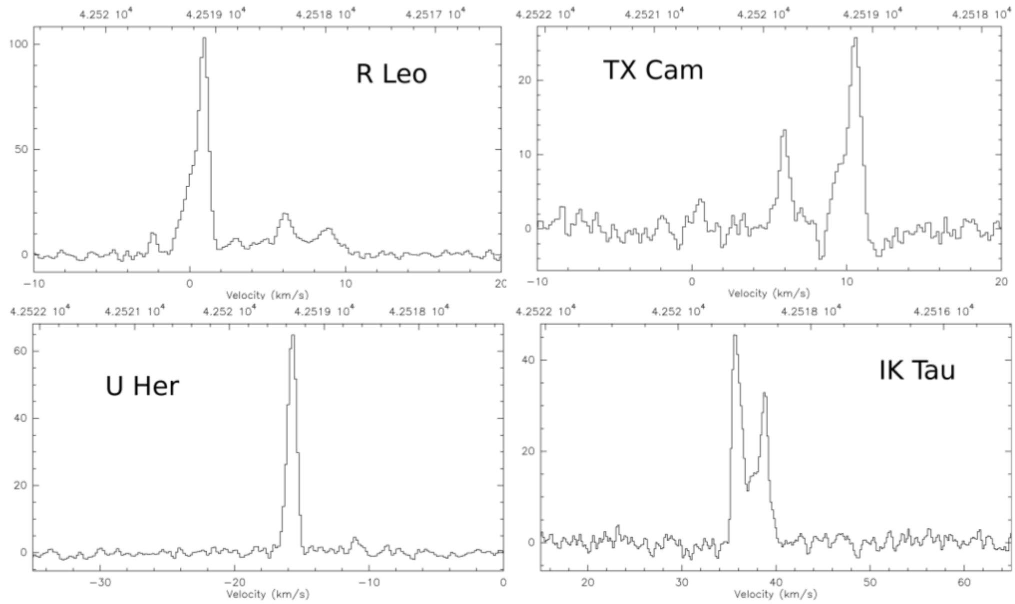

Figure 1: Onsala-20m spectra of the SiO J=1–0 v=3 maser emission from the AGBs stars R Leo, TX Cam, U Her, and IK Tau (The intensity scale is in Jy, velocity is w.r.t LSR)

2.2 VLBA observations

We have performed quasi-simultaneous[2] VLBA observations of the J=1–0 lines of ^{28}SiO from the three first vibrationally excited states v=1, 2, 3, respectively at 43.122, 42.820 and 42.519 GHz, in both circular polarizations. We reached an RMS noise in all the maps of about 5 mJy/beam per channel (with a frequency resolution of 0.2 km.s^{-1}). All maps were produced with a beam resolution of 0.5 mas.

In Figure 2 we show final maps of the brightness distribution of ^{28}SiO v=1, 2 and 3, J=1–0 (respectively drawn in blue, green, and red), obtained toward R Leo, TX Cam, U Her, and IK Tau. These are the first VLBA maps of the v=3 J=1–0 maser (using VERA, [10] recently observed the v=3 J=1–0 and published the maps of this line toward two AGB stars, WX Psc and W Hya, see also [9]). All maps show the typical clumpy emission, with the spots arranged in a sort of ring distribution.

As our observations were done using standard line observing mode, and not the phase referencing technique, the absolute positions of each maps was lost. The alignment of the maps presented in Figure 2 is just indicative. It follows criteria based on the similitude in velocity and the spatial distribution of the spots. As expected, the v=1, 2 J=1–0 lines arise from very similar areas, with a tendency of the v=2 spots to show up at locations somewhat closer to the center of the rings.

But the surprising result comes from the brightness distribution of the v=3 J=1–0. Despite what we were expecting, the spots of this maser are not located in a yet inner ring closer to the star, but their distribution is very similar to those of the v=1 and 2 J=1–0 masers, indicating that all three lines are inverted under very similar physical conditions.

[2]We periodically switched between two frequencies setup to observe the three lines.

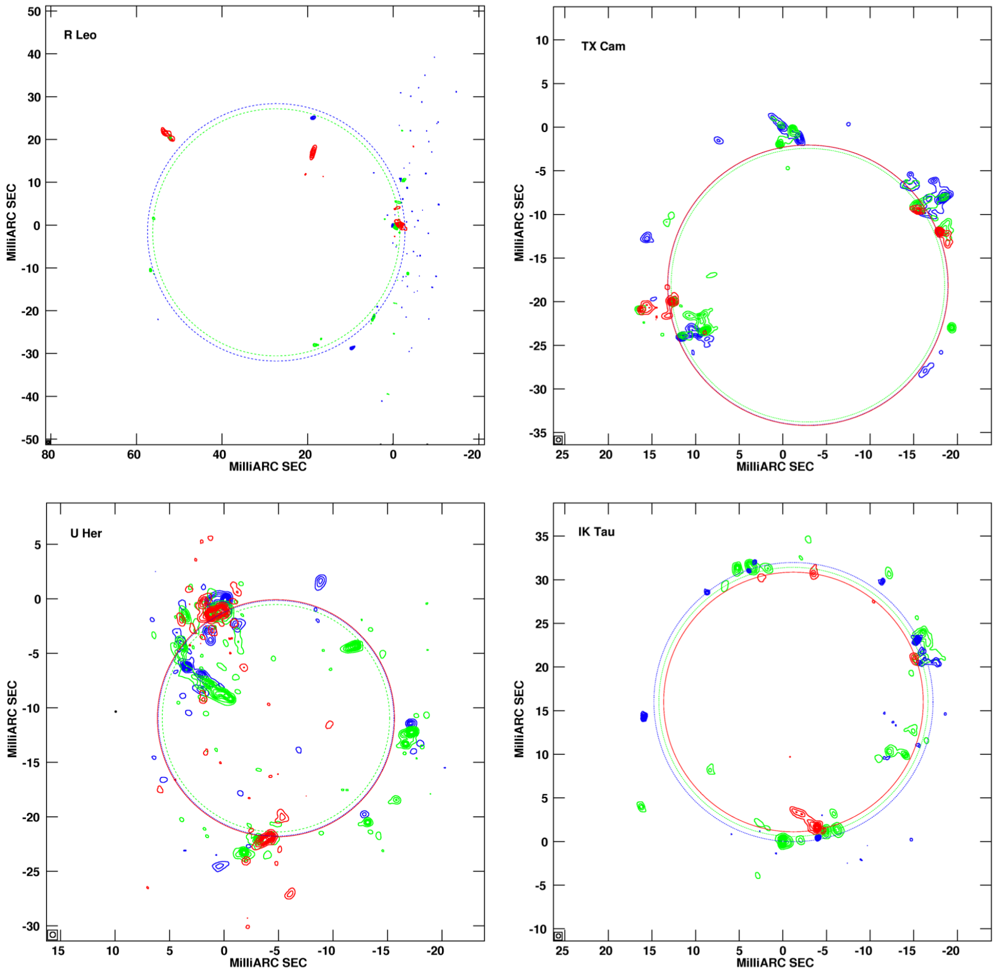

Figure 2: VLBA maps of SiO J=1–0 v=1 (in blue), v=2 (in green) and v=3 (in red) maser emissions from R Leo (upper left), TX Cam (upper right), U Her (lower left) and IK Tau (lower right). To ease the comparison between the three lines, we plotted the fitting rings (using the same color code) obtained with ODRpack for each maser transition (see [6] for more details).

Figure 3 shows a comparison between the intensities of the v=1, 2, 3 J=1–0 and J=2–1 maser lines, as function of the gas density according to our models (see [13]), without (left) and with (right) including the effects of the H_2O and SiO ro-vibrational line overlap. Note that without overlap, the masers from different vibrational states appear well separated tracing different physical conditions.

If we include the effects of the overlap, the v=3 J=1–0 is not affected and its emission conditions remains the same, but the v=1, 2 J=1–0 are affected and their masing conditions are modified. This is particularly true for the v=1. It's maser emission appears now covering a much wider range of density, increasing by nearly a factor $\sim$10, and notably, becoming possible at higher densities similar to those required for v=2 or v=3. The v=2 profile emission remains globally the same, but the maser emission is re-enforced by the overlapping (intensity increase by a factor of about 100),

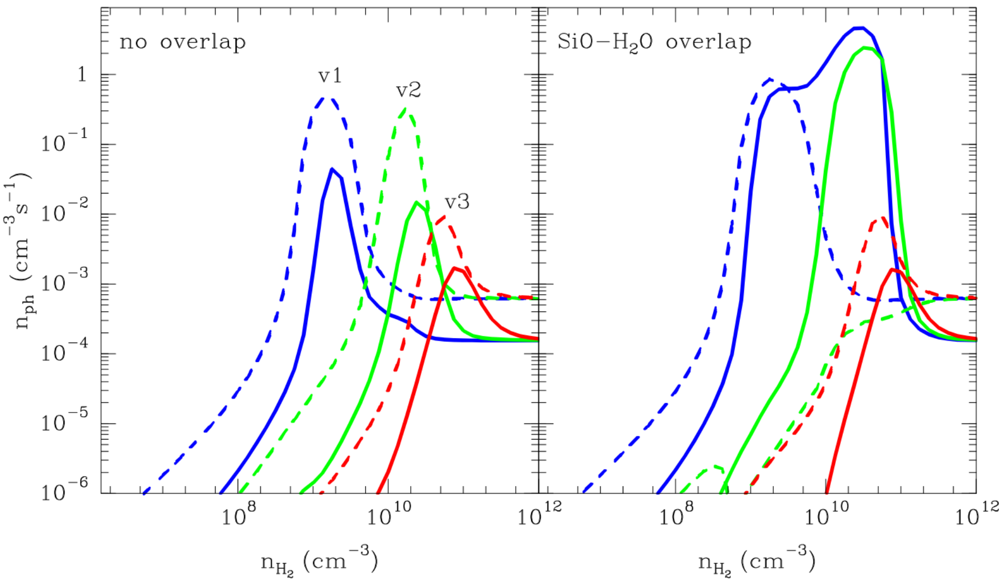

Figure 3: Effects of the H_2O line overlaps on the excitation of the SiO maser emission for the three first vibrationally excited levels, *v*=1, 2, 3 (respectively in blue, green and red) *J*=1–0 (solid line) and *J*=2–1 (dotted lines). On the left, we show results from models which neglect the effects of the line overlap. On the right, the same plot with line overlap included.

and the densities for masing are broadened by about a factor of 2-3, being the maximum of the emission somewhat moved to higher densities. This displacement to higher densities results in all three lines *v*=1, 2, 3 *J*=1–0, now showing their maximum emission under practically the same conditions (all three maxima occur within a factor 2 in density).

3. Conclusion

We have observed four AGB stars using the VLBA, and obtained reliable maps of *J*=1–0 SiO masers in the first three vibrationally excited states (*v*=1, 2, and 3). We observed that the brightness distribution of the *v*=3 maser do not show significant spatial distribution differences with respect to the maps that we obtained for the *v*=1 and 2 lines. The *v*=3 maser emission is distributed on ring-like pattern, coincident with, or slightly inner than, those of *v*=1, 2. Despite our initial believe, this is in agreement with model predictions only when the overlapping effects of two IR lines of SiO and H_2O are taken into account.

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