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^{28}SiO J=1-0, v=1, 2 & 3 maser emission from AGB stars

J.-F. Desmurs*
Observatorio Astronómico Nacional, Spain
E-mail: desmurs@oan.es

V. Bujarrabal
Observatorio Astronómico Nacional, Spain
E-mail: v.bujarrabal@oan.es

M. Lindqvist
Onsala Space Observatory
E-mail: michael.lindqvist@chalmers.se

J. Alcolea
Observatorio Astronómico Nacional, Spain
E-mail: j.alcolea@oan.es

R. Soria-Ruiz
Observatorio Astronómico Nacional, Spain
E-mail: r.soria@oan.es

P. Bergman
Onsala Space Observatory
E-mail: pbergman@chalmers.se

The v=1, 2 J=1–0 and v=1 J=2–1 are intense SiO masers, often mapped in AGB stars. Their distribution displays ring-like structures in the regions close to the star. The distribution of the v=1, 2 J=1–0 masers are similar, but the spots are rarely coincident. The v=1 J=2–1 maser arises, however, from a well separated region. It has been argued that this difference can only be explained by models including overlap of two IR lines of SiO and H_2O. The v=3 J=1–0 line is not expected to be affected by any line overlap, and its spot structure should be that predicted by the standard models.

Our first results on the relative positions of the three lines are surprising but yet consistent with current models including line overlap.

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*Speaker.

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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 VLBA ([6], [5], [4], etc). The maser emission is found to form a ring of spots at a few stellar radii from the center of the star. 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 [12], [13], [14]). In contradiction with predictions from both models (radiative and collisional), the v=1 J=2–1 maser spots systematically occupy a ring with a significantly larger radius (by 30%) than that of v=1 J=1–0, both spot distributions being completely unrelated. [12] 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 [12], this phenomenon, first proposed by [11] 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], [10], [7]), 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. We will see, however, that these intuitive ideas are not fully confirmed by detailed models calculations.

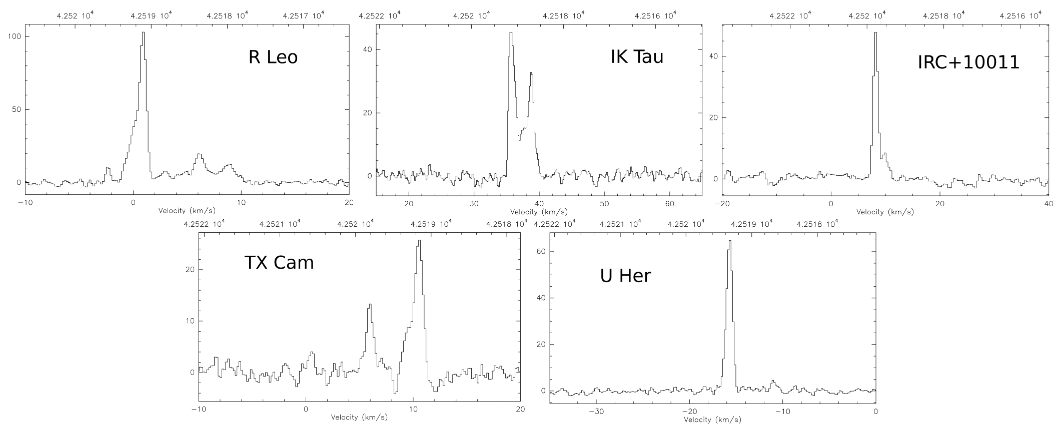

Figure 1: Onsala-20m spectra of the SiO J=1–0 v=3 maser emission from the AGBs stars R Leo, IK Tau, IRC+10011, TX Cam and U Her. (The intensity scale is in Jy.)

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 it 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 20 AGB stars using the 20-m antenna at Onsala at 43 GHz, 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}).

We detected several sources and we selected the five best candidates to be mapped with the VLBA. In Figure 1 we show the single dish spectra of the 5 best candidates: R Leo, IK Tau, TX Cam, U Her, and IRC+10011.

2.2 VLBA observations

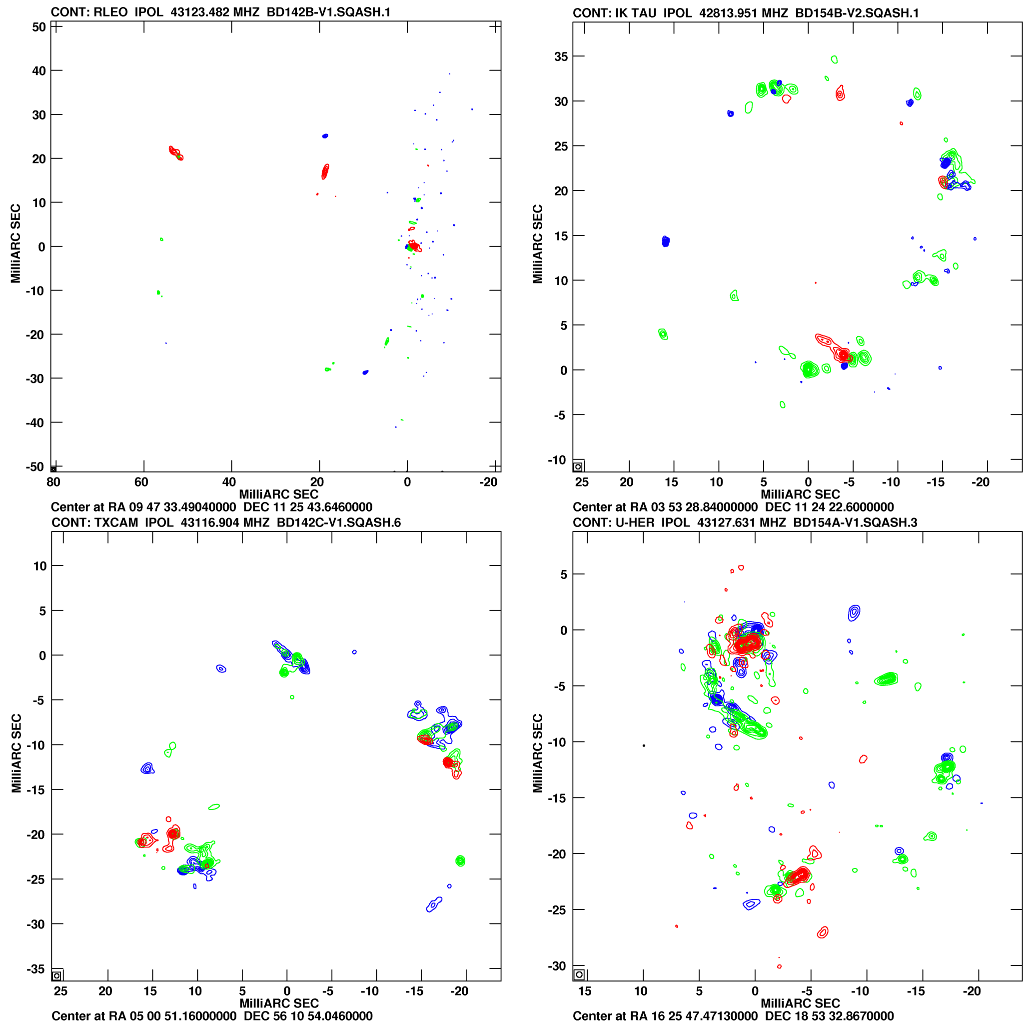

Figure 2: VLBA maps of SiO J=1–0 v=1 (in blue), v=2 (in green) and v=3 (in red) maser emissions from R Leo (upper left), IK Tau (upper right), TX Cam (lower left) and U Her (lower right)

We have performed quasi-simultaneous[1] 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 per channel (with a frequency resolution of 0.2 km/s). All maps were produced with a beam resolution of 0.5 mas.

In Figure 2 we show preliminary 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, IK Tau, TX Cam, and U Her. The map of IRC+10011 is not shown as it still presents some problems of phase calibration.

These are the first VLBA maps ever of the v=3 J=1–0 maser (using VERA, [9] 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 [8]). 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.

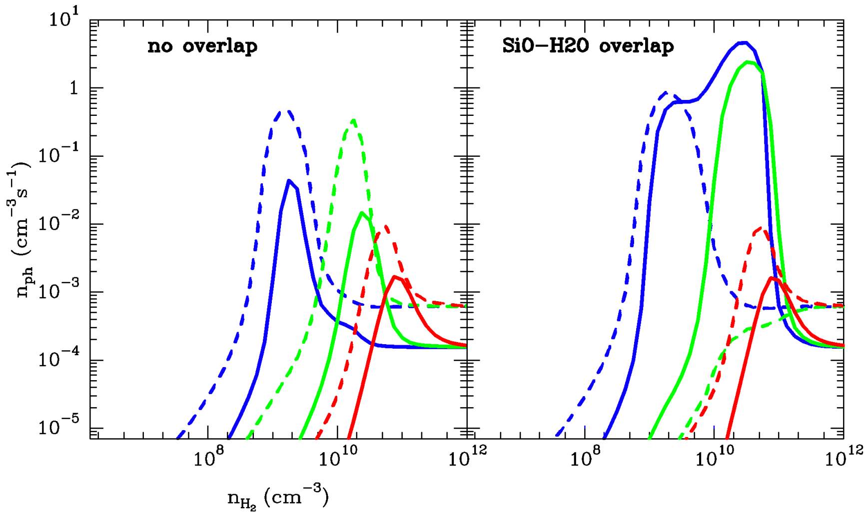

Figure 3: Effects of the H_2O line overlaps on the excitation of the SiO maser emission for the three first vibrationally excited levels, v=1, 2, 3 (respectively in blue, green and red) J=1–0 (solid line) and J=2–1 (dot lines). On the left, we show results from models not including the effects of the line overlap. On the right, the same plot with line overlap included.

But the surprising result comes from the brightness distribution of the v=3 J=1–0. Contrary to our expectations, 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 masers, indicating that all three lines are inverted under very similar physical conditions.

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

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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 [12]), 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 (in particular, density). 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, maser emission now appears covering a much wider range of density, increasing by nearly a factor ∼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), and the densities for massing 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.

3. Conclusion

We have observed 5 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) toward 4 of the sources. 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 or slightly inner than those of *v*=1, 2. Despite our initial believe, this is in agreement with model predictions, and can be easily explained by the wider range of density conditions giving rise to the *v*=1, 2 maser lines predicted when the overlapping effects of two IR lines of SiO and H_2O are taken into account.

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