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A study of the close environments of evolved stars from SiO masers

Valentín Bujarrabal[1], J. Alcolea[2], F. Colomer[1], J.-F. Desmurs[2], C. Sánchez Contreras[3], and R. Soria-Ruiz[4]

[1]Observatorio Astronómico Nacional, Apartado 112, E-28803 Alcalá de Henares, Spain
email: (v.bujarrabal,f.colomer)@oan.es

[2]Observatorio Astronómico Nacional, Calle Alfonso XII 3, E-28014 Madrid, Spain
email: (j.alcolea,jf.desmurs)@oan.es

[3]DAMIR, IEM, CSIC, Serrano 121, 28006 Madrid, Spain. email: carmen@damir.iem.csic.es

[4]JIVE, Postbus 2, 7990 AA Dwingeloo, The Netherlands. email: soria@jive.nl

Abstract. SiO maser emission allows us to study the innermost circumstellar layers around AGB and post-AGB stars, at a few AU from the stellar photosphere, what is crucial to understand the mass loss process in AGB stars and the jet launching mechanisms in post-AGB stars. Observations of SiO masers are also useful to address the question of the pumping mechanism itself, still under debate. In particular, VLBI observations of such emissions enables the study of the innermost shells with extremely high spatial resolution, equivalent (in nearby stars) to a few 10^{12} cm, about one tenth of the stellar radius. In this contribution, recent results on this topic obtained by our group are summarized.

Keywords. stars: AGB and post-AGB, circumstellar matter, stars: mass loss, stars: variables: long-period variables.

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1. General observational properties of SiO maser emission

Maser emission appears in SiO rotational lines, in general within vibrationally excited states. These lines are usually observed in evolved stars, mainly O-rich Mira-type variables. They are also detected in semi-regular and irregular variables, supergiant stars, S-type stars and a few proto-planetary nebulae around post-AGB stars (as well as in a few regions of star formation).

Many SiO maser lines have been detected, up to $J = 8$–7, in vibrational states up to $v = 4$. But the most intense and better studied transitions, by far, are $v = 1, 2$ $J = 1$–0 (43 GHz frequency, 7 mm wavelength) and $v = 1$ $J = 2$–1 (86 GHz). The $v = 2$ $J = 2$–1 line is known to be anomalously weak.

When we compare the emission of different stars, the SiO maser intensity depends on the amplitude of the stellar variability, being the high amplitude pulsators and the most intense emitters, e.g. Alcolea *et al.* (1990). The maser intensity also correlates very well with the IR stellar intensity, particularly at 8 μm, the wavelength of the $\Delta v = 1$ fundamental vibrational transition, see Bujarrabal *et al.* (1987).

More results from wide surveys of SiO maser emission can be found in the contribution by Deguchi (2007, these proceedings).

The rare isotopes ^{29}SiO and ^{30}SiO also present weak maser emission, but in them the masers usually appear in rotational transitions within the ground vibrational state. (Also lines from the vibrationally excited states of these species may be masers, but they are even weaker and more rarely detected.)

High resolution mapping of SiO masers, using VLBI techniques, show that the maser emission is in general distributed in rings of spots at a few stellar radii from the photosphere. Very probably, the maser formation is dominated by tangential amplification in the innermost circumstellar shells, in which the material is kept in levitation by shock energy dissipation, before the characteristic circumstellar expansion starts. Finally, polarization measurements show that the maser emission from each spot is linearly polarized, often in the tangential direction. Details on such measurements are discussed in the contribution by A. Kemball (Kemball 2007).

2. The pumping mechanisms of SiO masers from evolved stars

It is generally accepted that the main mechanism responsible for the inversion of the SiO masers is that proposed by Kwan & Scoville (1974). SiO maser emission usually appears in rotational lines within vibrationally excited states, therefore requiring a relatively high excitation degree, since the first vibrationally excited state is at 1800 K from the ground. The population of these $v > 1$ states from the fundamental one is followed by a fast radiative decay through the $\Delta v = 1$ transition. The mechanism by Kwan and Scoville is efficient when this transition is optically thick. Then, the efficient de-excitation probability of a given ro-vibrational component is proportional to $A\beta$, where A is its Einstein coefficient and β is the escape probability. In the optically thick case, $\beta \sim 1/\tau$. We also know that $\tau \underset{\sim}{\propto} A g_u$, where g_u is the statistical weight of the upper level; note that the variation of τ for the different rotational components of a given vibrational transition is largely dominated by this law in our case, in which a high rotational excitation can be assumed.

Therefore, the efficient probabilities of the different components are essentially proportional to $1/g_u$. This means that the molecules are relatively more trapped in levels with higher J-values, though the effect is vanishingly noticeable for consecutive levels with very high Js. In other words, the appearance of high opacities in the $\Delta v = 1$ de-excitation tends to produce a systematic inversion of the rotational transitions in the upper v-state. A chains of masers so appears that are mutually reinforced, because the molecules decaying to one rotational level strengthen the maser from that level to the lower next one.

The mechanism responsible for the population of the vibrationally excited states, i.e. the final energy source of the maser radiation, is still debated. The $v > 1$ level population could be radiative or collisional. In any case, the excitation of lines lying at least at 1800 K from the ground requires a high excitation environment, and all models place the masers very close to the stellar photosphere.

The collisional pumping mechanism is relatively simple and only requires efficient collisional population of the excited states, because it is known that the collisional population itself does practically not select the rotational levels. A great theoretical and computational effort has been devoted to those models (e.g. Lockett & Elitzur 1992, Humphreys *et al.* 2002), including a detailed modeling of the shock fronts traversing the masing region.

On the other hand, radiative pumping is somewhat more complex and requires that the exciting radiation field is anisotropic (essentially coming from the central star or close surroundings, e.g. Bujarrabal 1994). These conditions naturally lead to the tangential maser amplification and linear polarization deduced from the observations. Radiative models are also supported by the observed correlation of the SiO intensity with the IR stellar continuum. We will discuss below the comparison of the variations of the maser and continuum fluxes during the stellar cycle, found to be remarkably in phase.

3. SiO maser variability

Very soon after their discovery, it was realized that SiO masers are variable, as it is expected from the nature of the emission. Because of the few SiO masers detected in regions of massive star formation, the variability of the SiO maser emission in these type of sources is very scarcely studied. On the contrary, the properties of SiO masers in long period variables are fairly well known thanks to numerous monitoring studies, of which the most complete in many senses is the one carried out at 7 mm ($J = 1$–0) with the 13.7 m dish at Yebes (see Pardo *et al.* 2004 with references therein and a full listing of all other monitoring works on SiO maser variability). The Yebes monitoring started in 1984 and ended in 1995, so in the best cases we have data for a period of 11 yr. The typical spacing between observations is 3 weeks. This spacing was set to properly sample the typical time scale of the SiO maser variations in regular (Mira-type) variables, which was known to present periods of about one year. Initially, the monitoring included 14 sources that were only observed in the $v = 1$ line. Later more sources and the $v = 2$ line were added. Since 1989, 20 long-period variables and Orion A were observed in the two $J = 1$–0 transitions. In total the monitoring comprises more than 3500 spectra, taken under an special procedure to ensure a relative calibration better than 10%.

This monitoring represents a major improvement with respect to previous similar works, and in fact it is the only one in which its length and tight spacing allow a time-series analysis of the data, resulting in the first and so far only quantitative estimates of the variability properties of SiO masers. In addition, the data were combined with optical and/or infrared monitoring of the central stars, which were also subject to time-series investigations. These analysis showed that, al least in Mira variables, the three types of emission (SiO, optical and NIR) have the same dominant period of variability, within $\pm 4\%$: the period of the pulsation of the star. In addition, it is also found that SiO maxima happen accurately in phase with NIR maxima, phase lags $\lesssim 0.05$ in absolute value, and with a positive phase lag typically between 0.05 and 0.20 with respect to optical maxima. The presence of regular variability in other SiO maser parameters, such as the mean velocity, was also investigated with no significant results. For the non-Mira variables in our sample, the time-series analysis yielded no clear trends except for GY Aql. This object is considered to be a semi-regular variable but the SiO properties are very similar to those of Mira stars. In fact the SiO period found in our data for this source coincides with the optical period derived from optical data obtained during the last part of our monitoring.

All these results indicate a tight and universal SiO/NIR phase coincidence, making a strong case in favor of radiative pumping of SiO masers, which explains such a correlation in a very natural way. On the other hand, collisional dominated models require a very fine ad hoc tuning on a case by case of the shock front properties, in order to explain such a tight coincidence.

4. The relative distribution of the maser spots for different transitions

4.1. $v = 1$ $J = 1$–0 *vs.* $v = 2$ $J = 1$–0

The first attempts to measure the relative positions of two SiO maser lines were performed by Miyoshi *et al.* (1994), who mapped the $v = 1, 2$ $J = 1$–0 lines. These authors concluded that both transitions appeared spatially coincident, but with a relatively poor resolution. It was also concluded that such a coincidence strongly favored collisional pumping. Both collisional and radiative mechanisms require generally different conditions to excite these lines, because they belong to different vibrational states and require different excitation

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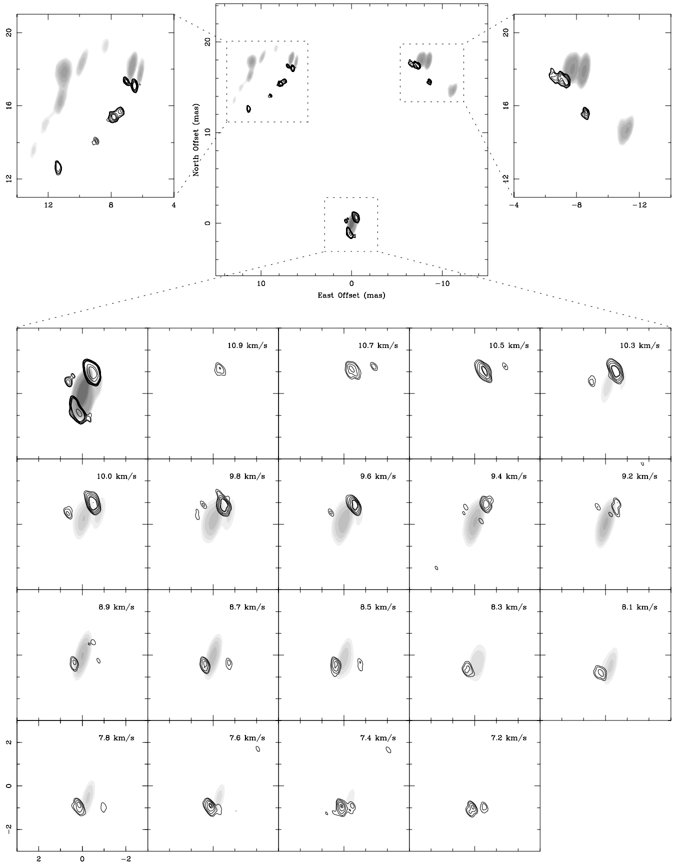

Figure 1. Maps of $v = 1$ and 2, $J = 1$–0 maser emission (respectively, grey scale and contours). From Soria-Ruiz *et al.* (2004).

degrees. Under the radiative schemes, it is more difficult that both lines are intense simultaneously.

However, observations with much higher resolution (Desmurs *et al.* 2000) have shown that, in fact, the spots of the $v = 1$ $J = 1$–0 and $v = 2$ $J = 1$–0 transitions are almost never coincident, although the overall distributions are similar. In general, the $v = 2$ 43 GHz transition appears slightly, but systematically closer to the central star, by 1 or 2 mas.

In some cases, one has the impression that each transition avoids the other. We can see an example in Fig. 1, Soria-Ruiz *et al.* (2004), which shows observations of the very red AGB star IRC +10011. In the southern clump, the $v = 2$ emission in some way moves around the $v = 1$ clump, depending on the velocity, but avoiding a true coincidence.

We see another example of this behavior in Fig. 2, which represents observations of the same source at a later epoch. Other VLBI observations of the relative positions of these lines have been published by Cotton *et al.* (2004, 2006), confirming the above conclusions.

4.2. $v = 1$ $J = 1$–*0* *vs.* $v = 1$ $J = 2$–*1*

The $v = 1$ $J = 2$–1 transition is also a strong maser, but VLBI data are scarce, because of its relatively high frequency, 86 GHz.

The first maps of this line have revealed a surprising result. The emitting spots at 86 GHz show a completely different distribution than those of $v = 1$ $J = 1$–0, see Soria-Ruiz *et al.* (2004, 2005) and Fig. 2. Here, we cannot say that there are small shifts

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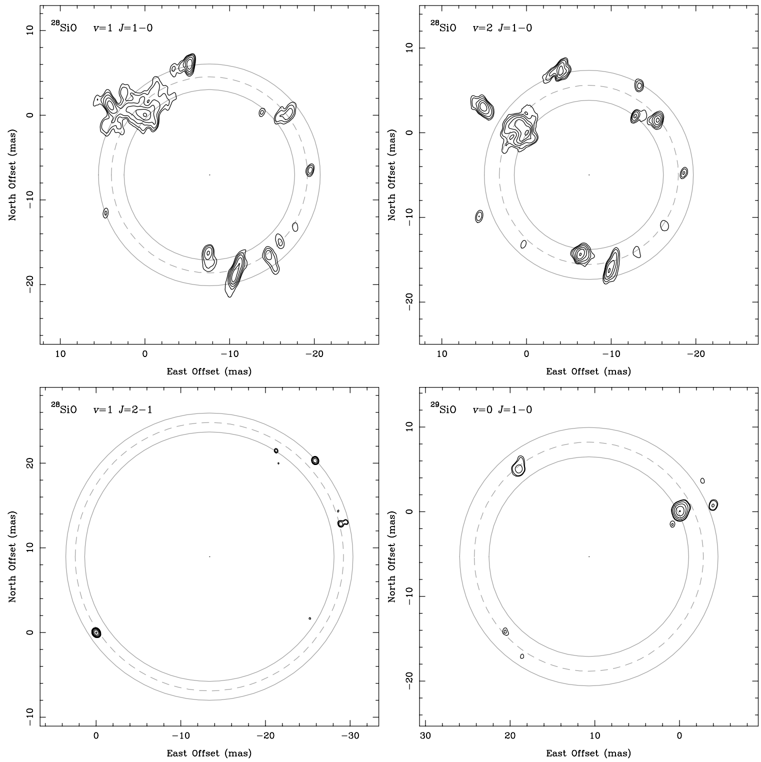

Figure 2. Integrated intensity maps for SiO maser emissions in IRC +10011. Circles denote the ring fitting of the masering regions. From Soria-Ruiz *et al.* (2005).

between the spots: the distributions of both lines are clearly different. In the few cases observed, the $v=1$ $J=2$–1 emission is always placed significantly outwards with respect to the 43 GHz rings.

This relative distributions were completely unexpected because, as mentioned (Sect 2), the $v=1$, $J=1$–0 and $J=2$–1 transitions belong to the same rotational ladder and require very similar pumping conditions. In fact we expected the formation of chains of masers in strong coupling. This result is then in clear contradiction with the standard, usually accepted theory; we will see (Sect. 5) that the presence of line overlap may explain such a behavior.

4.3. ^{29}*SiO*, $v=0$ $J=1$–*0*

The results from the maps of the ^{29}SiO, $v=0$ $J=1$–0 masers are also surprising. This line (the most intense maser line of the rare isotopes) requires a very low excitation. In fact, the standard models for this maser, place it quite far from the star, yielding in particular a dominant radial amplification (Robinson & Van Blerkom 1981, Deguchi & Nguyen-Q-Rieu 1983).

However, the observed distribution of the ^{29}SiO, $v=0$ $J=1$–0 spots is similar to that of the other masers; see Fig 2, Soria-Ruiz *et al.* (2005). One would say that the distribution of this line is *too similar* to those of the other masers we have mentioned, although identical to none of them.

It has been proposed that line overlap effects could also explain these observations.

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5. Effects on the maser pumping of line overlap

Line overlap occurs when two lines have almost identical frequencies, such that, taking into account the local or macroscopic velocity dispersions, both line profiles significantly overlap. Then, the photon field available to one of the lines is affected by the emission or absorption by the other. The anomalously weak maser in the $v = 2$ $J = 2$–1 transition could be explained by the overlap between the H_2O $v_2 = 0, 12_{7,5} - v_2 = 1, 11_{6,6}$ and the ^{28}SiO $v = 2$, $J = 1 - v = 1$, $J = 0$ ro-vibrational components (Olofsson *et al.* 1985). The H_2O line would increase the number of photons available for the SiO component, leading to a relative overpopulation of the $v = 2$ $J = 1$ level and quenching the (otherwise intense) $v = 2$ $J = 2$–1 maser, provided that the water component is emitting a sufficiently high number of photons.

This overlapping pair could also explain some of the observations presented above, see details in Soria-Ruiz *et al.* (2005), Bujarrabal *et al.* (1996). The overpopulation of the $v = 2$ $J = 1$ level appears at the same time as a relative under-population of the $v = 1$ $J = 0$ level, therefore establishing a strong coupling between the $v = 1$ $J = 1$–0 and $v = 2$ $J = 1$–0 lines. Both emissions would then appear in relatively similar regions. Meanwhile, the $v = 1$ $J = 2$–1 one would now require different conditions than those for the 43 GHz transitions. Detailed calculations presented by Soria-Ruiz *et al.* (2005) explain, at least qualitatively, all the observational properties of the relative spatial distributions of these lines.

Line overlap could also explain the main properties of the ^{29}SiO, $v = 0$ $J = 1$–0 maser emission. In this case, two ro-vibrational components of SiO would overlap: ^{28}SiO $v = 2$, $J = 4 - v = 1$, $J = 3$ and ^{29}SiO $v = 1$, $J = 1 - v = 0, J = 0$. The strong ^{28}SiO line would excite the ^{29}SiO ro-vibrational component, yielding an under-population of the ^{29}SiO $v = 0$ $J = 0$ level. This would explain the $v = 0$ $J = 1$–0 maser, without invoking other mechanisms. The fact that strong vibrational emission of ^{28}SiO is required also explains that the ^{29}SiO maser only appears in high-excitation regions, even if the ^{29}SiO line itself is close to the ground level.

We note that overlap has been proposed to explain other maser lines of ^{29}SiO and ^{30}SiO, but theoretical results are not always conclusive.

6. SiO masers in proto-planetary nebulae (PPNe)

SiO masers have also been detected around a few post-AGB stars. The best studied one, by far, is OH 231.8+4.2. This source is a peculiar PPNe, an elongated bipolar nebula surrounding a double star.

SiO masers in OH 231.8+4.2 show a characteristic three-peak structure that has persisted during more than ten years, in spite of changes in the relative intensity or shape of the peaks (Sánchez Contreras *et al.*, private communication; Fig. 3). It is improbable that this profile is just due to a random clump distribution, since in ten years clumps moving at the measured velocities should in general leave the small emitting region (see mapping data below). The three-peak profile must be a property of some stable structure, like a rotating disk. This profile shape is in fact expected from Keplerian disks (see Deguchi 1993, Elitzur 2007), independently of the exact density distribution in them.

Recent VLBI mapping of SiO maser emission in OH 231.8+4.2 (Sánchez Contreras *et al.* 2002, Desmurs *et al.* 2007a,b) shows that this emission comes from an elongated structure in the center of the nebula, perpendicular to the symmetry axis. Although only two peaks were detected, the derived spatial distribution and velocities are consistent with emission coming from a rotating structure.

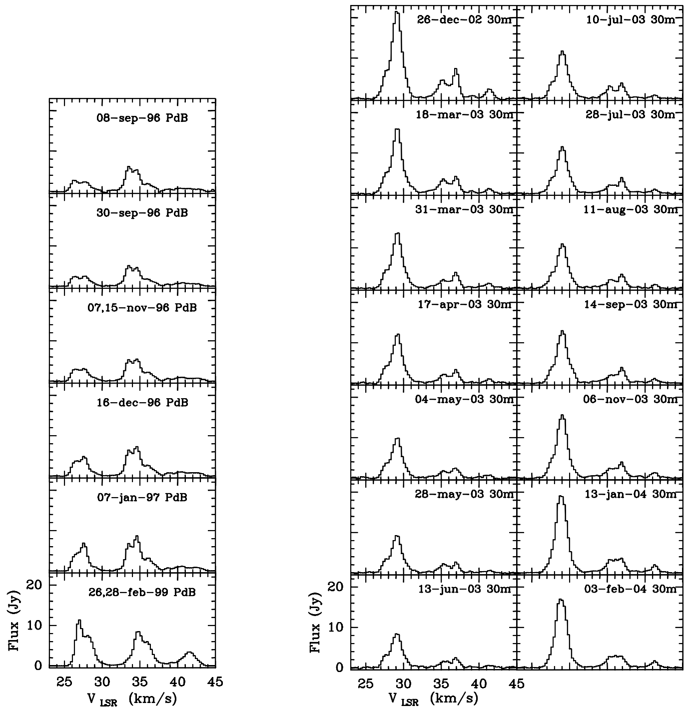

Figure 3. Time variation of the $v = 1$ $J = 2$–1 maser emission in OH 231.8+4.2. Data from the Plateau de Bure (PdB) and 30m telescopes are presented.

The combination of both the single-dish observations and the VLBI mapping argue in favor of that SiO masers in OH 231.8+4.2 identify a very small disk (diameter $\sim 10^{13}$ cm), kept in rotation by gravitation around a stellar mass of about 1 $M_{\odot}$.

The detection of central Keplerian disks in PPNe is particularly important. The presence of jets in post-AGB stars is thought to be the leading mechanism in the shaping of planetary nebulae: a phenomenon that involves an impressive shock dynamics, which accelerates, in just a few hundred years, a gas mass of $\sim 1/2\ M_{\odot}$ up to almost 100 km s^{-1}. It is usually assumed that re-accretion of circumstellar material, through the formation of a rotating disk, is the most probable mechanism to explain such ejections. (See e.g. Bujarrabal *et al.* 2001, Frank & Blackman 2004.) However, these disks have been only well detected to date in one PPNe, the Red Rectangle, from thermal CO emission. In other sources, the disks could be too small to be mapped in thermal emission, with resolutions $\sim 1''$. The reason is probably that the requirement of angular momentum to form big enough disks, that must come from a close stellar or substellar companion, is too strong and only satisfied in relatively massive stellar systems. VLBI observations (of maser emission) can attain much higher resolutions and then detect much smaller disks, for which the angular momentum problem is much less severe. We think that the detection of rotating disks around post-AGB stars from SiO maser data can be a key observational tool to disentangle the actual association of Keplerian disks with jets in these objects.

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