Recent High Resolution Studies of Maser Emission

© F. Colomer[1], V. Bujarrabal[2]

[1]Instituto Geográfico Nacional, Spain
[2]Observatorio Astronómico Nacional, Spain

Microwave amplification by stimulated emission of radiation (maser) processes are common in the Universe. These can be found in star formation regions, in circumstellar envelopes (CSEs) around evolved stars (mainly around AGB and post-AGB stars), in our and other galaxies. Since the maser emission is bright and compact, high resolution VLBI observations are a basic tool to study their distribution and other characteristics, therefore providing useful information to derive physical conditions in the regions where they occur.

The advent of recent technological developments and instruments make now possible to study cosmic masers not only in a more efficient way, but also opens new scenarios for modeling of the emission. In particular, observations of several maser lines simultaneously provide unique information to constrain pumping models.

Keywords: VLBI, astronomical masers.

1 Masers in late-type stars

Late–type stars in the Asympthotic Giant Branch (AGB) deploy a circumstellar envelope (CSE) rich in molecules; Fig. 1 sketches the different layers and approximate location of molecules and masers which are being studied by VLBI, mostly in the case of O–rich envelopes.

1.1 SiO masers

Observations of SiO masers performed in various vibrational and rotational transitions by very long baseline radiointerferometric techniques (VLBI) have provided extremely valuable information on the spatial structure and dynamics of the inner circumstellar shells around AGB stars.

VLBI mapping systematically shows emission clumps distributed in a ring-like structure consistent with tangential ray amplification at about 10^{14} cm from the star (equivalent to about 2 stellar radii). The structure and dynamics of the SiO inner shells have been studied in great detail with the VLBA instrument for the

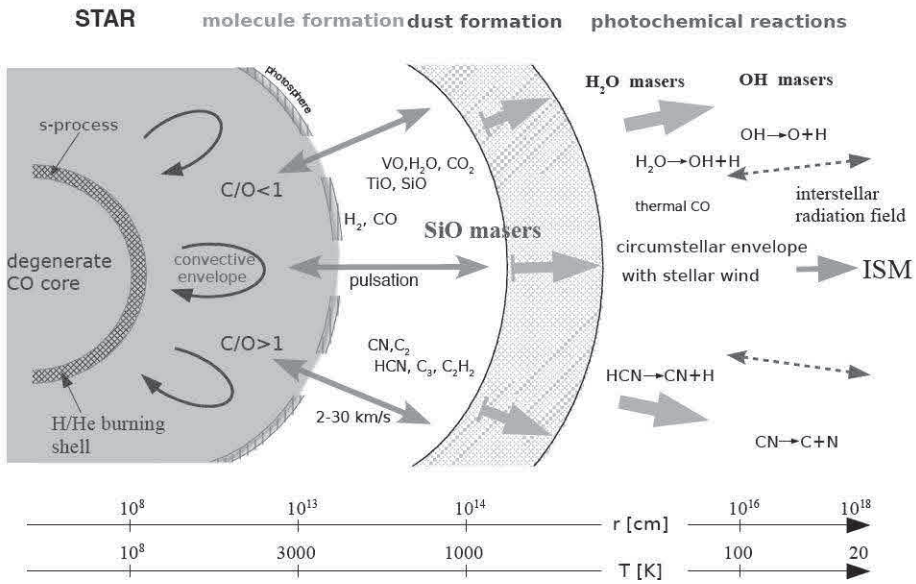

Fig. 1. Diagram of the circumstellar envelope structure in AGB stars

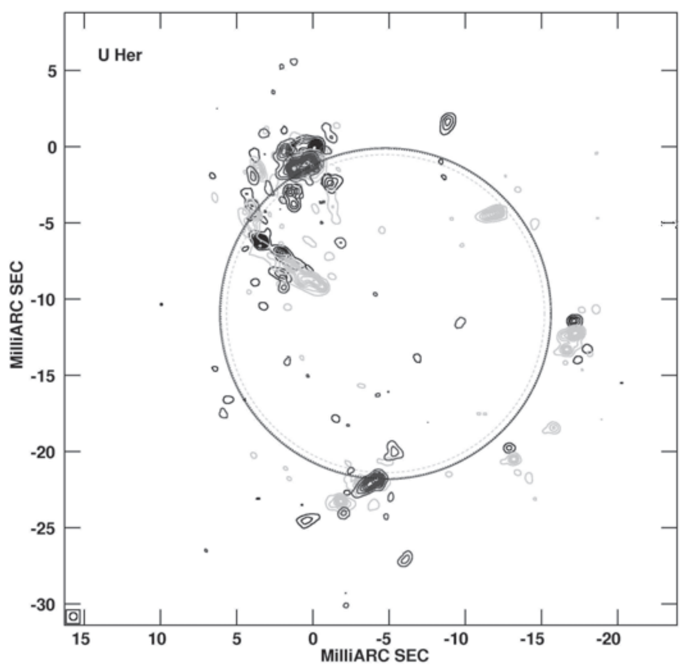

Fig. 2. Map of SiO maser $J = 1 \rightarrow 0$ $v = 1, 2, 3$ emission in the circumstellar envelope of the AGB star U Her [11]

43 GHz ($\lambda = 7$ mm) of the SiO $J = 1 \rightarrow 0$ maser lines in the $v = 1$ and $v = 2$ vibrationally excited states at a resolution of about 2 10^{12} cm for the typical distance to these objects (see e. g. [27] [10] [12] [13] [38] [39] [17] [2] [11]). Comparing the observed brightness distributions in different vibrational/rotational states should be indicative of which excitation mechanisms dominate. The $v = 1$, 2 $J = 1 - 0$ maser lines often occupy similar regions, but their clumps are rarely spatially coincident and the $v = 2$ emission ring tends to be closer to the star. Recent observations by KaVA (the combined Korean Very Long Baseline Interferometry Network, KVN, and the Japanese VLBI Exploration of Radio Astrometry, VERA) confirm this scenario by precisely deriving maser spot positions from astrometric analysis [42].

The SiO $J = 2 - 1$ lines, around 86 GHz ($\lambda = 3$ mm), are often strong masers, especially in the $v = 1$ state, but they have been much less studied with VLBI techniques than the $J = 1 \rightarrow 0$ lines [3] [7] [8] [14] [38]. The standard theoretical models predict that the $v = 1$ $J = 1 \rightarrow 0$ and $v = 1$ $J = 2 \rightarrow 1$ lines, with nearby energy levels and thus requiring a similar pumping mechanism, must come from the same clumps (e. g. [28] [6]). However, observations of AGB stars such as IRC+10011, R Leo and χ Cyg have shown that these two lines exhibit a ring morphology but are not coincident at all. In fact, the $J = 2 \rightarrow 1$ maser clumps occupy a clearly larger shell in the circumstellar envelope ([38] [39]; see also R Cas data in [33]). In this complex scenario, new detailed and sensitive mapping of the SiO lines undertaken with the most sensitive interferometric baselines will bring very useful information.

1.1.1 Models of SiO maser emission

The comparison of models of SiO emission (including models combining SiO excitation and dynamic evolution of circumstellar atmospheres) with VLBI data and single dish SiO observations allows to specify the physical conditions in the circumstellar environment of late-type stars and to discern the main mechanisms at work for the vibrational/rotational excitation of the SiO molecule. A lot of work has been devoted to theoretically understand the pumping of SiO masers since they were discovered. The basic mechanism responsible for the population inversion is thought to be the presence of photon trapping in the radiative deexcitation $v \rightarrow v - 1$ [26]. Discrepancies in the source of energy responsible for the vibrational excitation still persist and have been widely discussed in the bibliography (since [15] and [5]; the pumping can be collisional or radiative, due to absorption of stellar photons). Other theoretical aspects have been also developed, notably the angular distribution of the maser emission from the shocked inner shells [24] and the effects of line overlap of two infrared lines of SiO and water that affects the SiO maser pumping [38].

The very clumpy spatial distribution was studied in detail [18], using a very sophisticated code that takes the effects of shocks on the masing clumps into account. In particular, the treatment of the radiative pumping was improved with respect to previous calculations. The agreement with the observations is satisfactory. However, some aspects are still to be developed, mainly the comparison with the observed periodical variations, the apparently too low predicted brightness (in comparison with that of the very compact observed spots), and the appearance of strong spots at short angular distances from the center. Efforts to improve this study are being done [19], and relevant results are expected in the near future.

New calculations [11] also aim to better understand the effects of line overlap on the pumping of the different maser lines of ^{28}SiO. Line overlap seems to be a basic phenomenon to explain the observed properties and models explain, at least qualitatively, the observed total intensities and spatial distributions of all lines (which are being accurately measured only recently because of the need of very good relative astrometry), in particular, they allow to reconcile the 43 and 86 GHz observed maser distributions. These models, however, do not include the important clumpiness actually observed in VLBI maps. The effects of overlap on the pumping of masers of ^{29}SiO and ^{30}SiO, which are particularly intense in the $v = 0$ state and not understood to date, still require a deep study.

1.2 Water masers

New data from the Atacama Large Millimeter Array (ALMA) on VY CMa enabled to locate sub-mm water masers with milli-arcsec accuracy and to resolve the dusty continuum [36], and may help to understand the dynamics of the winds from the pulsating stellar surface to 10 stellar radii, where radiation pressure on dust is fully effective. The 658, 321, and 325 GHz masers are found located in irregular, thick shells at increasing distances from the centre of expansion, which is confirmed as the stellar position. The maser shells overlap but avoid each other on scales of up to 10 AU, and while their distribution is broadly consistent with excitation models, the conditions and kinematics are complicated by wind collisions, clumping, and asymmetries. Nevetheless, these observations provide the opportunity to test sub-mm maser models rigorously.

Through polarization observations, masers are good probes of the magnetic field in the envelopes of late-type stars, although interpretation is delicate. Observations of the polarization of H_2O masers provide such information in an intermediate density and temperature region [41], showing field strengths of the order of several Gauss. Large scale magnetic fields permeate the circumstellar envelope around VX Sgr and reveals a dipole field structure. The magnetic field may be coupled with the stellar outflow, possibly causing aspherical mass-loss and participating in the bipolar structures of post-AGB objects.

1.3 Open issues

The study of circumstellar masers may be in a golden age, thanks to the availability of new instruments that provide very accurate (even astrometric) positioning of the emission, which can be then related to the distribution of other lines or molecules. KaVA can now provide multiline simultaneous data [42], and ALMA sensitivity allows the detection of the AGB photosphere, which till now was performed only in special cases [34]. In this scenario, it may be possible soon to reveal what is the reason for the large SiO missing maser flux in VLBI baselines, as compared with single dish data; whether it is due to the existence of many tiny and weak spots that are still undetected, or due to larger regions of emission that are resolved out [9]

Also, HCN masers can be strong in C-rich AGB circumstellar envelopes; however no detections have been reported yet by VLBI [1].

2 Masers in star forming regions

Many interesting results are being provided by instruments like VERA, in combination or cooperation with the EVN and VLBA. A multiepoch VLBI study of 22 GHz H_2O masers in the Orion KL region detected the annual parallax to be 2.29 ± 0.10 mas, corresponding to a distance of 437 ± 19 pc from the Sun, a much more accurate value than previously obtained, with an uncertainty of only 4 % [22]. VERA operates a dual-beam receiving system, therefore provides the needed phase-referencing VLBI astrometry. In addition, absolute proper motions of the maser feature suggest an outflow motion powered by the radio Source I. ALMA can map the emission of SiO in Orion KL in the frequency range from 214 to 246 GHz (^{28}SiO $v = 0$, 1, 2 and ^{29}SiO $v = 0$, and ^{28}Si^{18}O $v = 0$), showing an extended bipolar shape in the northeast-southwest direction that indicates that these emissions trace an outflow that is driven by the embedded high-mass young stellar object (YSO) [32] [16]. Whereas on small scales (10–1000 AU) the outflow from Source I has a well-ordered spatial and velocity structure, as probed by VLBI imaging of SiO masers [31], the large scales (500–5000 AU) probed by thermal SiO with ALMA reveal a complex structure and velocity field, most likely related to the effects of the environment of the BN/KL region on the outflow emanating from Source I. A narrow spectral profile and spatial distribution of the SiO $v = 1$ $J = 5 \rightarrow 4$ line provide evidence for maser emission associated with Source I; this will enable studies of the Source I disk-outflow interface with future longest baselines.

A hundred trigonometric parallaxes and proper motions for masers associated with young, high-mass stars have been measured with the VLBA (Bar and Spiral Structure Legacy Survey KSP), the EVN and VERA [35] [23]. These measurements provide strong evidence for the existence of spiral arms in the Milky Way, accurately locating many arm segments, with the widths of spiral arms increasing with distance from the Galactic center. The distance to the Galactic center is estimated to be 8.34 ± 0.16 kpc, and the circular rotation speed at the Sun to be 240 ± 8 km/s, and a rotation curve that is nearly flat. The accuracy of the results would significantly reduce the uncertainty in tests of gravitational radiation predicted by general relativity.

The combination of gas and stellar astrometry (as being provided by Gaia) will be a powerful tool to distinguish several dynamical models of galaxy rotation. VERA astrometry on IRAS 07427-2400 place the source at 5.41 kpc, in the Perseus arm, the nearest main arm in the Milky Way [37]. Systematic deviation from circular rotation is seen; model selection between those proposed by the density-wave theory and the recurrent transient spiral proposed by mainly numerical simulations will allow to understand the origin and evolution of the spiral arm, as well as those of the Milky Way.

Methanol class II masers at 6.7 GHz are well known tracers of high-mass star-forming regions. However, their origin is still not clearly understood. Studies with the EVN have provided high sensitivity images for 63 sources with milliarcsecond angular resolution [4], determining the morphology and velocity structure as ring-like, rotating and expanding disks, or a bipolar outflow. In the data, typically, 50–70 % of the flux is missing when comparing the interferometric and single-dish spectra, a phenomena which is not strongly related to the distance of the source (i. e. is not only effect of spatial resolution).

Finally, the first VLBI imaging of a 44 GHz class I methanol maser, IRAS 18151-1208, performed using KaVA, is found to be associated with the MM2 core, which is thought to be less evolved than another millimeter core MM1 associated with the 6.7 GHz class II methanol maser [30]. Attempts to detect Methanol Class-I masers at 95 GHz with VLBI have not been successful so far [29].

3 Masers in other galaxies

Water megamasers can be used to test the unified model in AGNs, the need of a torus, and the physics of the AGN central engine; actually they currently provide the only way to map the structure of circumnuclear accretion disks within a parsec of AGN supermassive black holes.

ALMA has detected the first extragalactic submillimeter H_2O maser in the 321 GHz transition toward the center of Circinus galaxy [21]. By comparing the velocities of the maser features in this and the known 22 GHz H_2O maser transition, it can be deduced that they occur in similar regions, those already revealed by VLBI. The detected maser features remain unresolved at the ALMA synthesized beam size (~ 15 pc at the source) and coincide with the 321 GHz continuum peak within small uncertainties. An interesting but still tentative detection of a high velocity feature in the galaxy suggests, if it would arise from the well known Keplerian rotating disk, that the molecular material closest to the central engine can be probed.

Maser distance estimations can also be used to measure H_0 accurately, and constrain dark matter. VLBI observations of the active galaxy NGC 4258 provided maser line-of-sight velocities and sky positions [25], allowing to measure a distance of 7.60 Mpc with only a 3 % uncertainty. The resulting Hubble constant, based on the use of the Cepheid variables in NGC 4258 to recalibrate the Cepheid distance scale, is $H_0 = 72.0 \pm 3.0$ km s^{-1} Mpc^{-1}. The method can be used for more redshifted galaxies, were other lines can appear into regions of good atmospheric transmission.

SiO, H_2O and OH masers in AGB stars on the Magellanic Clouds have been used to study dust formation and mass-loss under low–metallicity conditions [40]. No significant differences between Galactic and MC CSEs were found.

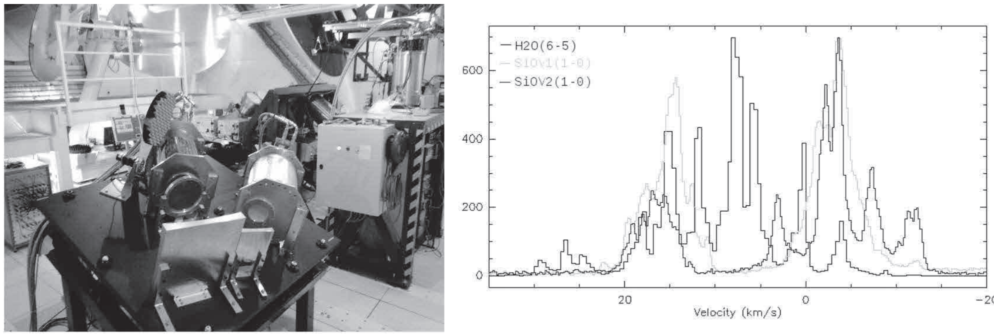

Fig. 3. Left: Receivers installed at the Yebes 40-m radio telescope that allows the simultaneous observation of the frequency bands centered at 22 and 43 GHz. Right: example of obtained spectra

4 Multifrequency observation scenarios

A new scenario for multiline studies arises thanks to the technological development in broadband receivers and the capability to perform simultaneous observations in different frequency bands. One very successful case is KVN [20]), where a setup of receivers centered at 22, 43, 86 and 129 GHz allow to study H_2O and several lines of SiO at the same time. This instrument is producing a great advance in the observational field of masers in AGBs (see the many maps of SiO in e. g. [42]). However it lacks very long baselines; in this respect we have installed a system at the IGN Yebes 40-m radio telescope (in Guadalajara, Spain) that allows the simultaneous observation of the frequency bands centered at 22 and 43 GHz (see Fig. 3). The receiver for 86 GHz is expected to be installed shortly, which will enhance the technical capabilities for this kind of studies.

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