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Unveiling fine details of the (giga)maser source in TXS2226-184 with the VLBI

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In nearby and distant active galactic nuclei (AGNs), water (mega)masers can be used to determine the accretion disk geometry and precise black hole masses, and standard-candles-independent distances to the host galaxy (*disk-masers*), to provide important information about the evolution of jets (*jet-masers*), and to trace the velocity and geometry of nuclear winds (*outflow-masers*). In the following, we report on the main outcome of our recent study, performed with the VLBA and EVN networks, of the water gigamaser in TXS2226-184. Our analysis indicates an association of the maser emission with a luminous radio knot in the nuclear region of the galaxy, seemingly part of a large scale radio jet, hence supporting a jet/outflow nature of the maser. In addition, we present new multi-frequency radio-continuum EVN observations of the innermost region of TXS2226-184 aimed at gaining a clearer picture of the nuclear individual components of the AGN and determining a more precise location of the supermassive black hole SMBH.

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1. Introduction

Water (mega)masers in AGNs are associated with: i) accretion disks around supermassive black holes (e.g., [1]); ii) radio jets (e.g., [2]); iii) nuclear outflows/dusty tori (e.g., [3]). Individually, each source represents a goldmine of information on the nuclear region and AGN activity. So far, about 3500 galaxies have been surveyed in a search for 22-GHz water maser emission. Only 180 water maser sources have been found ([4]). In particular, they have been detected in radio quiet galaxies, mostly classified as Seyfert 2's or LINERs, in the local Universe (z < 0.05), with some exceptions like, e.g., 3C403 (an FRII at z=0.06; [5], [6]), MG J0414+0534 (a type 1 quasar at z=2.64; [7], [8]). Overall detection rates are of a few percent (see, e.g., [9], [4], [10]), and hence, besides the discovery of new maser sources, more detailed studies of already known megamasers, are crucial for a better understanding of the dynamics and physical processes in AGNs (see, e.g., [11] for Circinus; [12], [13] and [14] for NGC1068).

2. The gigamaser in TXS2226-184: past and present.

TXS2226-184 is located at a distance of 107.1 Mpc ([15]). It has been optically classified as an elliptical/S0 galaxy ([16]), even though [17] proposed an alternative classification as a possible later-type galaxy. Furthermore, TXS 2226-184 is spectroscopically identified as a LINER ([18]). The water megamaser in TXS2226-184 was first detected in 1995 and its emission was so bright (6100 solar luminosities) that the source was labeled as 'gigamaser' ([16]). High angular resolution measurements were reported in a conference proceeding on 2005, only ([19]), although no absolute position was measured for the maser spots. Indeed, surprisingly, since its discovery in the mid-nineties, this exceptionally luminous source has never been studied into great details. Therefore, in 2017, we acquired new three-epochs K-band observations with the VLBA (first epoch) and EVN (second and third epochs) networks. The first two epochs were observed in phase-reference mode, while the last one was observed in full-polarization mode, but not in phase-reference mode to increase the on-source integration time ([20]).

In our observations, the maser emission is resolved into 6 maser features forming a linear/arc structure without a regular velocity gradient (Fig. 1). Neither continuum nor polarized emission is detected down to a level of 0.2 mJy/beam and 15%, respectively. Indeed, for the first time, we derived the absolute position of the maser features and compare it with the VLBI radio continuum maps available from [21]. The maser features are associated with the most luminous radio continuum clump reported by [21]. The outcome of this study is reported into detail in [20].

3. The nature of the gigamaser in TXS2226-184

There are a number of clues in favor of either a disk or a jet/outflow origin of the maser emission in TXS2226-184.

In favor of the latter nature is the single broad line profile of the feature without any apparent sign of the paradigmatic three well-separated groups of features. On the contrary, the long-term stability of the emission over two decades is not typical of jet/outflow masers (although in a few cases stable emission has been found, like, e.g., the maser in MGJ0414+0534 at z=2.64; [7]; [8]), thus

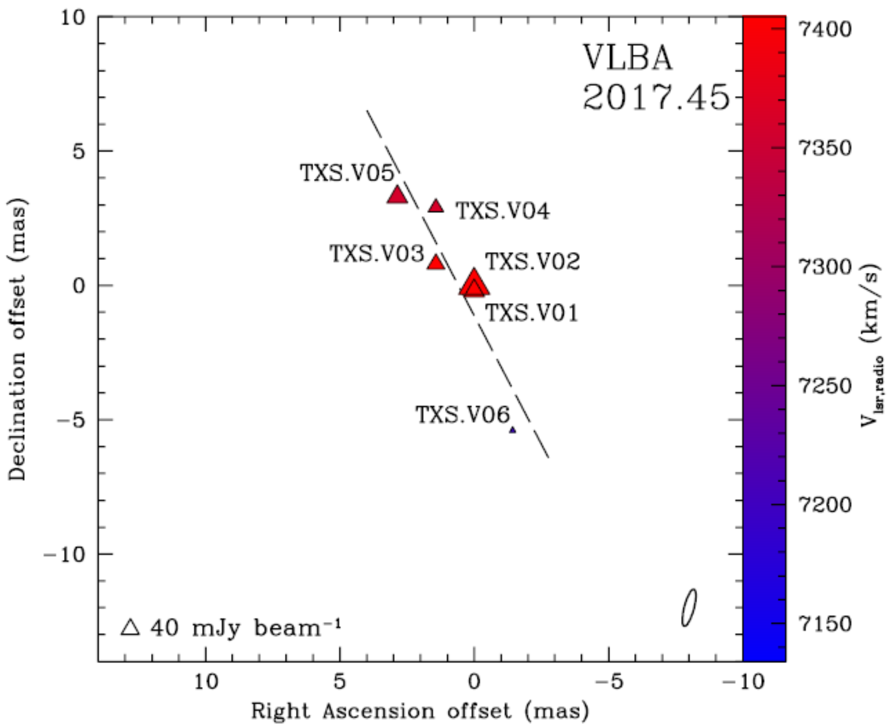

Figure 1: View of the H_2O maser features detected toward TXS 2226-184 with the VLBA. Triangles identify H_2O maser features whose side length is scaled logarithmically according to their peak flux density. The 40 mJy/beam symbol is plotted for comparison in both panels. Maser local standard of rest radial velocities are indicated by color (the lsr velocity - radio convention - of the galaxy is 7270 km s^{-1}). The beam size (HPBW) is shown in the bottom right corner. At the distance of the galaxy (107.1 Mpc) 1 mas corresponds to $\sim$ 0.5 pc. The dashed line is the best least-squares linear fit of the maser distribution (PA_{H_2O} = +28° ± 12°). Figure taken from [20].

may hint at a different nature. Given also the linear distribution of the spots, it may be associated with a disk.

In order to draw a definite conclusion, however, a key question has to be addressed: where is the actual location of the nucleus/SMBH? In order to answer this question, new observations have been acquired that are described in the following section.

4. New VLBI measurements: observations, main results and preliminary discussion

Between February and March 2021, we observed the core of TXS2226-184 with the EVN+eMERLIN array at L, C, and K band. The details of the observations are reported in Table. 1. Only the data of the two lowest frequencies were reduced, so far, by using standard routines implemented in the NRAO software AIPS. A preliminary analysis has been performed using both the AIPS and KARMA software.

Radio continuum maps at 1.6 and 5 GHz have been produced and are shown in Figs. 2 and 3.

When comparing our L-band map with that from [21], the first striking difference is the lack of the strong and diffuse emission to the SE corner of the map (see Fig. 2). The reason for such

Table 1: Details of the new EVN observations of the radio continuum in TXS2226-184 and of the maps produced.

Date (mm-dd-yyyy)	Frequency (GHz)	Obs. Setup	Obs. Time (hrs)	HPBW (mas)	Map noise (mJy/beam)
02-26-2021	1.6	4×32 MHz, 2 pols.	7.0	30×15	0.05
03-07-2021	5	8×32 MHz, 2 pols.	7.0	5×4	0.03
03-09-2021	22	8×32 MHz, 2 pols.	7.0	N/A *	N/A*

* Data still under reduction

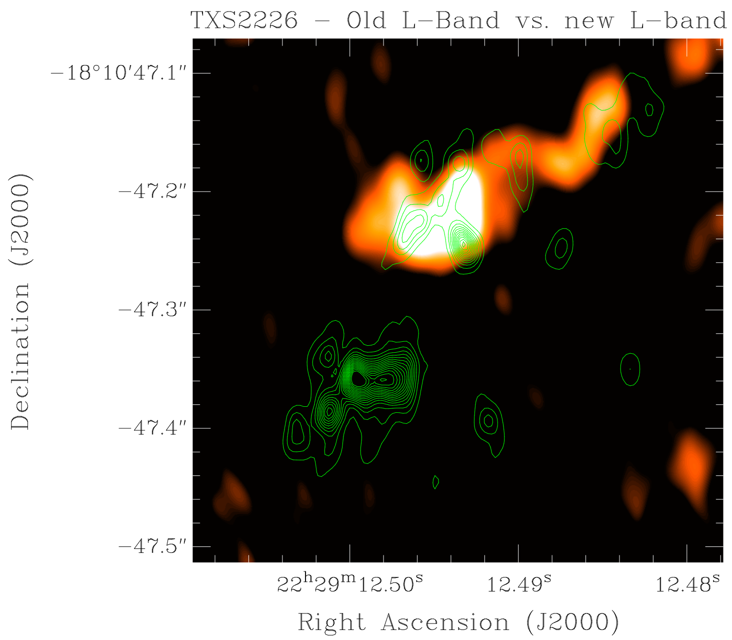

Figure 2: Combination of the naturally-weighted new EVN 1.6 GHz radio continuum map (HPBW: 30×15 mas) of the nuclear region of TXS2226-184 (color scale) with the VLBA 1.4 GHz (HPBW: 20×12 mas) contour map, as observed in 2002 by [21] (their Fig. 2). Contours (in green) are drawn at 1, 2, 4, 6, 8, . . ., 26 × 3σ, where σ = 43.23 µJy/beam. A 20 mas angular size correspond to 10 pc at the distance of the galaxy.

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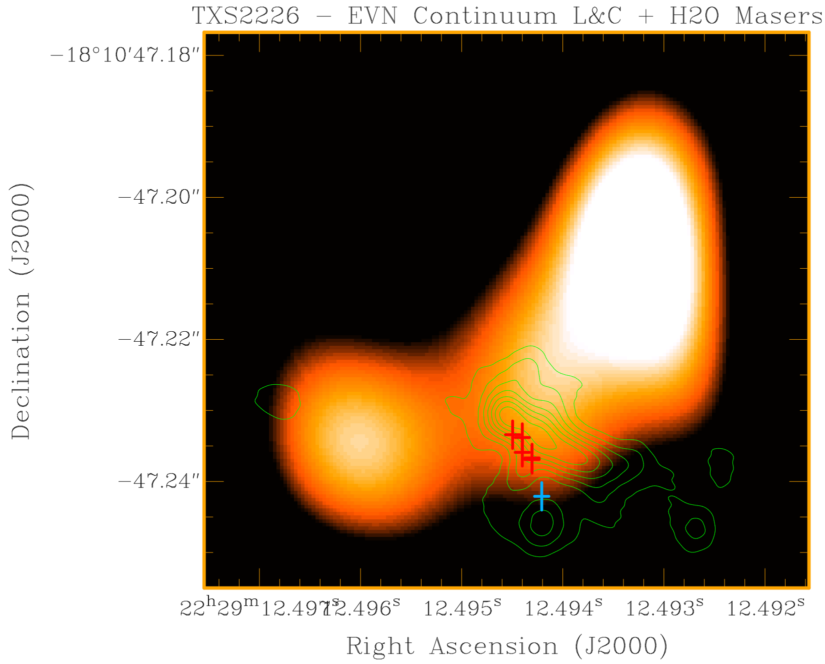

Figure 3: Combination of the naturally-weighted 1.6-GHz new EVN radio continuum map (HPBW: 30×15 mas) of the (zoomed) nuclear region of TXS2226-184 (color scale) with the naturally-weighted 5-GHz new EVN contour map (HPBW: 5×4 mas) overlaid. Contours (in green) are drawn at -1, 1, 2, 3, 4, 5, 6 × 3σ, where σ = 30 µJy/beam. Crosses (red and blues) indicate the position of the maser features detected with the VLBA by [20]. A 20 mas angular size correspond to 10 pc at the distance of the galaxy.

an absence is presently under discussion. Possible hypotheses include the fading of a jet-knot or a transient nature of the emission.

Taking into consideration the slightly different resolution, the remaining emission is consistent with that reported in literature by [21], although some evolution seems to be present.

From the new maps (Fig.3), it is evident that the spectral index is highly inverted at the location of the maser and where the optical depth (as derived by [21]) is the largest. This may indicate that the nucleus (taken as the SMBH or base of the jet) is actually coincident with the maser emitting region. If this is the case, the option that the maser is associated with a jet knot offset from the nucleus is not any longer viable, while the options remain valid of a maser nature related to the base of the jet, to a 'peculiar' accretion disk, or to the inner region of the dusty torus.

5. Summary and follow-ups

Individually each (mega)maser is a unique tool to derive detailed information on AGN (accretion disks, jets/outflows, and molecular tori) and estimate fundamental astronomical quantities, such as distances and masses of SMBHs. As a class, megamasers provide a very relevant support, especially together with observations in different bands (e.g., IR, mm/sub-mm, X-ray, etc.). It allows us to understand the dynamics and physical processes in AGNs and to verify the Unified Model.

For the case of TXS2226-184, our VLBI studies allowed us to: i) detect the maser spots with (sub)mas accuracy and derive their absolute position; ii) produce multi-frequency continuum maps of the nuclear region; iii) help shedding light on the possible maser origin, likely associated with the base of the jet, a 'peculiar' accretion disk, or the inner edge of the dusty torus.

Eventually, the interpretation on the nature of the (giga)maser in TXS2226-184 will surely benefit from our ongoing effort to create a model of the innermost regions of the galaxy to be compared with the scenario inferred from the reported VLBI line and continuum observations.

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