Cosmic Masers: Proper Motion toward the Next-Generation Large Projects
Proceedings IAU Symposium No. 380, 2024
T. Hirota, H. Imai, K. Menten, & Y. Pihlström, eds.
doi:10.1017/S1743921323002077

What's behind the corner: Maser emission in nearby and distant galaxies with the new radio facilities

Andrea Tarchi[1], Paola Castangia[1], Gabriele Surcis[1], Elisabetta Ladu[1,2] and Elena Yu Bannikova[3,4]

[1]INAF-Osservatorio Astronomico di Cagliari, Via della Scienza 5, 09047, Selargius (CA), Italy. email: andrea.tarchi@inaf.it

[2]Department of Physics, University of Cagliari, S.P.Monserrato-Sestu km 0,700, I-09042 Monserrato (CA), Italy

[3]INAF - Astronomical Observatory of Capodimonte, Salita Moiariello 16, Naples I-80131, Italy

[4]Institute of Radio Astronomy, National Academy of Sciences of Ukraine, Mystetstv 4, Kharkiv UA-61002, Ukraine

Abstract. Extragalactic maser sources are unique tools to derive fundamental physical quantities of the host galaxies, e.g, geometry of accretion disks around super-massive black holes and precise black hole masses, and study in detail the interaction region of nuclear jets/outflows with the interstellar medium, in nearby and distant Active Galactic Nuclei. So far, however, extragalactic maser searches have yielded detection of few percent, and only relatively few maser sources have been found. Because of their unprecedented sensitivity, new upcoming facilities, like the SKA and the ngVLA, will allow to significantly increase the number of known (water) maser sources. This will lead to the chance of performing statistically-relevant studies of the maser phenomenon (and its occurrence), derive extragalactic masers luminosity functions, and ultimately (in particular, through the aid of longer-baselines arrays options) to perform the studies described above for larger samples and up to cosmological distances.

Keywords. masers, galaxy:active, galaxy:individual (TXS2226−184)

1. Introduction

H_2O masers associated with active galactic nuclei (AGN, the 'megamasers') have been related with three distinct phenomena: (i) nuclear accretion disks, where they can be used to derive the disk geometry, enclosed nuclear mass, and distance to the host galaxy (see, e.g., Braatz *et al.* 2010 for UGC 3789), or sometimes with the inner boundary of a dusty torus in the region of the interaction with the outflows (e.g.,Bannikova *et al.* 2023, for NGC1068); (ii) radio jets, where can provide important information about the evolution of jets and their hotspots (e. g. Peck *et al.* 2003 for Mrk 348, and, more recently, Castangia *et al.* 2019, for IRAS 15480); (iii) nuclear outflows, tracing the velocity and geometry of nuclear winds at < 1 pc from the nucleus, as in the case of Circinus (Greenhill *et al.* 2003) and NGC 3079 (Kondratko *et al.* 2005), where they offer a promising means to probe the structure and motion of the clouds in the Toroidal Obscuring Region (TOR) predicted by clumpy torus models (e.g., Nenkova *et al.* 2008). In all these cases, water megamasers provide vital information on the structures, dynamics and composition of the molecular gas at close proximity to the AGN.

2. Recent (VLBI) studies by our team

Our group is presently leading a number of (VLBI) studies focused on a few promising extragalactic maser sources in order to exploit the information obtained in the framework of a better understanding of the unified scheme for AGN. In particular, the main targets are:

• the jet-maser in the nucleus of the Seyfert 2 galaxy IRAS15480−0344, detected in a sample that has provided one of the highest maser detection rate (50%), and followed-up in a recent survey with the SRT (for details, see P. Castangia's contribution, this volume);

• the luminous maser in the LINER galaxy IC 485, for which our recent EVN and VLBA observations hint at a disk maser nature, possibly accompanied by a jet/outflow maser component (for details, see Elisabetta Ladu's contribution, this volume);

• the nuclear gigamaser in TXS 2226-184 where, for the first time, the location of the H_2O masers w.r.t. the continuum emission has been obtained (see following sections)

2.1. *The gigamaser in TXS2226−184*

TXS2226−184 has been optically identified as an elliptical/S0 galaxy (Koekemoer *et al.* 1995), even though Falcke *et al.* (2000) proposed a different classification as a possible later-type galaxy. Furthermore, it is spectroscopically classified as a LINER (Bennert *et al.* 2004). TXS 2226-184 is located at a distance of 107.1 Mpc (Kuo *et al.* 2018) and, in this galaxy, a water megamaser was first detected in 1995, whose emission was so bright (6100 solar luminosities) that the source was labeled as gigamaser (Koekemoer *et al.* 1995). High angular resolution measurements were reported only in a conference proceeding on 2005 (Ball *et al.* 2005), although no absolute position was measured for the maser spots. More recently, Surcis *et al.* (2020) reported that the maser emission is resolved into 6 maser features forming a linear/arc structure without a regular velocity gradient (Figure 1). Neither continuum nor polarized emission at 22 GHz is detected down to a level of 0.2 mJy/beam and 15%, respectively. The maser features are associated with the most luminous radio continuum knot reported by Taylor *et al.* (2004) at 1.4 GHz. In order to draw a definite conclusion on the maser nature, however, a key question has to be addressed: where is the actual location of the nucleus/SMBH?

2.2. *Where is the nucleus in TXS2226−184?*

On February and March 2021, we observed the nuclear region of TXS2226−184 with the EVN+eMERLIN array at L, C, and K band. So far, only the data of the two lowest frequencies were calibrated, and a preliminary analysis performed.

The new maps (Figure 1) makes evident that the spectral index is highly inverted at the location of the maser and where the optical depth (as derived by Taylor *et al.* 2004) 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 most likely option for the maser nature is related to the base of the jet, to a peculiar accretion disk, or to the inner region of the dusty torus (Tarchi et al. in prep).

3. Great expectations for extragalactic maser studies

Despite each megamaser source represents a goldmine of information on the nuclear ejection/accretion activity of the host galaxy, overall maser detection rates are of only a few percent. Indeed, out of about 3500 galaxies surveyed, only 180 water maser sources have been found, mostly in radio quiet AGN, mostly classified as Seyfert 2s or LINERs, in the local Universe ($z < 0.05$; Braatz *et al.* 2018). Therefore, more sources are needed for detailed studies, maser luminosity functions, and statistical considerations.

https://doi.org/10.1017/S1743921323002077 Published online by Cambridge University Press

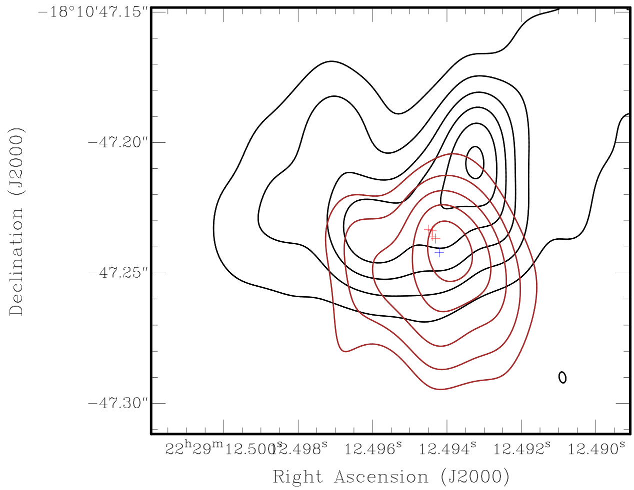

Figure 1. L and C bands EVN contour maps of the nuclear radio continuum emission of TXS2226−184. The C-band data have been convolved to the same resolution of the L-band data (HPBW: 30×15 mas). Contours at 1.6 GHz (in black) are drawn at 0.2, 0.4. 0.6. 0.8, ..., 1.6 mJy/beam. Contours at 5 GHz (in brown) are drawn at 1.5, 2.0, 2.5, 3.0, 3.5, 4.0 mJy/beam. Red and blue crosses indicate the maser positions as derived by Surcis *et al.* (2020).

3.1. *Targetted searches*

Taking profit of their enhanced sensitivity w.r.t. existing radio telescopes, the SKA and the ngVLA will be able to deliver relevant results by performing targeted searches of extremely large samples of galaxies. The spectral-line sensitivity (a few mJy in an 1-km/s wide channel) typically sought for with a 100-m class single-dish (i.e., the antennas that are typically used in water maser searches) will be reached by the aforementioned facilities in a factor 10 less time, thus allowing to search (with comparable sensitivity) much larger samples. This will yield the detection (and, possibly, the simultaneous sub-arcsecond position, useful for VLBI studies) of many more objects locally and, also when considering that the water maser luminosity function (LF) is a relatively steep power-law, of a still significant number of maser sources also at larger distances (up to z ∼0.5) and, seemingly, in classes of galaxies where, so far, no maser have been found.

3.2. *Blind searches*

When approaching cosmological distances $z \geq 1$, blind surveys of water maser sources with the SKA and the ngVLA may also become extremely profitable, particularly if, as reported in the literature, the LF evolves with redshift by $(1+z)^m$ (with $m =$ 4, or 8). Under this latter assumption, as shown in Figure 2, also blind searches with these new facilities would already yield, at $z \geq 1$, a significant number of expected masers, when areas of the order of a square degree is attained. This is surely feasible thanks to the enhanced sensitivity and the large field of view of the aforementioned arrays, and together with the large instantaneous bandwidths (∼ 2.5 GHz) available, that allow one to cover all at once relevant redshift ranges.

Needless to say, in order to maximize the return of any new maser detection and, more generally, to exploit masers as tools to derive fundamental information on AGN (and not only), as those described in the previous section, high-angular resolution studies (mainly with VLBI) are mandatory. In this framework, the option offered for the SKA

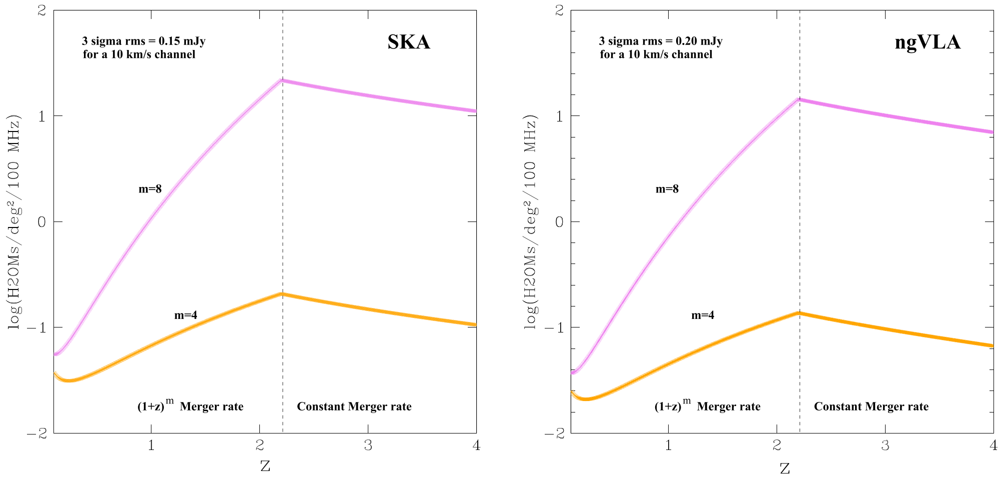

Figure 2. Density of detectable water masers as a function of redshift (0.1$\leq z \leq$4) with the SKA-1 MID (left) and ngVLA (right) arrays, assuming a LF evolution, increasing with redshift by (1+z)^m, with m equal to 4 or 8 up to z =2.2, and then becoming constant. The values are computed considering a survey covering an area of a square degree and an integration time of 15 hours per pointing (Tarchi et al. in prep.).

and the ngVLA to access baselines as long as, at least, those presently provided by the main existing VLBI networks becomes indispensable, especially given that an increased sensitivity will be offered by the arrays as a whole.

References

Ball, G.H., Greenhill, L.J., Moran, J.M., Zaw, I., Henkel, C. 2005, *ASP Conf. Ser.*, 340, 235
Bannikova, E. Yu, Akerman, N., Capaccioli, M., *et al.* 2023, *MNRAS*, 518, 742
N. Bennert, H. Schulz, & C. Henkel, 2004, *A&A*, 419, 127
Braatz, J.A., Reid, M.J., Humphreys, E.M.L, *et al.* 2010, *ApJ*, 718, 657
Braatz, J.A.; Condon, J., Henkel, C., *et al.* 2018, *IAUS*, 336, 86
Castangia, P., Surcis, G., Tarchi, A., *et al.* 2019, *A&A*, 629, 25
Falcke, H., Wilson, A.S., Henkel, C., Brunthaler, A., Braatz J.A. 2000, *ApJ*, 530 L13
Greenhill, L.J., Booth, R.S., Ellingsen, S.P., *et al.* 2003, *ApJ*, 590, 162
Koekemoer, A.M., Henkel, C., Greenhill, L.J., *et al.* 1995, *Nature*, 378, 697
Kondratko, P.T., Greenhill, L.J., & Moran, J.M. 2005, *ApJ*, 618, 618
Kuo, C.Y., Constantin, A., Braatz, J.A., *et al.* 2018, *ApJ* 860, 169
Nenkova, M., Sirocky, M.M., Nikutta, R., Ivezić, Z., Elitzur, M. 2008, *ApJ*, 685, 160
Peck, A. B., Henkel, C., Ulvestad, J.S., *et al.* 2003, *ApJ*, 590, 149
Surcis, G., Tarchi, A., & Castangia, P. 2020, *A&A*, 637, 57
G.B. Taylor, A.B. Peck, J.S. Ulvestad, C.P. ODea 2004, *ApJ*, 612, 780

https://doi.org/10.1017/S1743921323002077 Published online by Cambridge University Press