Astrophysical Masers:
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H_2O MegaMasers: RadioAstron success story

Willem Baan[1,2], Alexey Alakoz[3], Tao An[4], Simon Ellingsen[5], Christian Henkel[6,7], Hiroshi Imai[8], Vladimir Kostenko[3], Ivan Litovchenko[3], James Moran[9], Andrej Sobolev[10] and Alexander Tolmachev[3]

[1]Netherlands Institute for Radio Astronomy, Dwingeloo, The Netherlands,
email: baan@astron.nl
[2]XinJiang Astronomical Observatory, Chinese Academy of Sciences, Urumqi, PR China
[3]AstroSpace Center, Lebedev Physical Institute, Moscow, Russia,
email: alexey.alakoz@gmail.com
[4]Shanghai Astrophysical Observatory, Chinese Academy of Sciences, Shanghai, PR China
[5]University of Tasmania, Hobart, Australia
[6]Max Planck Institut für Radioastronomie, Bonn, Germany
[7]Astron. Dept., King Abdulaziz Univ., Jeddah, Saudi Arabia
[8]Kagoshima University, Kagoshima, Japan
[9]Center for Astrophysics, Cambridge MA, USA
[10]Ural Federal University, Ekaterinburg, Russia

Abstract. The RadioAstron space-VLBI mission has successfully detected extragalactic H_2O MegaMaser emission regions at very long Earth to space baselines ranging between 1.4 and 26.7 Earth Diameters (ED). The preliminary results for two galaxies, NGC 3079 and NGC 4258, at baselines longer than one ED indicate masering environments and excitation conditions in these galaxies that are distinctly different. Further observations of NGC 4258 at even longer baselines are expected to reveal more of the physics of individual emission regions.

Keywords. galaxies: nuclei, galaxies: ISM, masers, radio lines: ISM

1. Introduction

The Space Radio Telescope or the RadioAstron Observatory (RAO) is an international space-VLBI project led by the Astro Space Center of PN Lebedev Physical Institute. The RadioAstron payload on board of the Spectr-R mission has been equipped with a 10 meter antenna, two hydrogen masers, and receivers in P, L, C, and K-band (Kardashev *et al.* 2013). This paper presents some recent results of RAO observations of H_2O MegaMasers (MM) using the highest window of the Multi-Frequency Synthesis (MFS) system at 22 GHz, which covers a redshift range z = 0.0 - 0.0053 for H_2O MM emission studies. A total of 24 known H_2O MM have a redshift falling within this window but only 7 of them are deemed strong enough for detection with RadioAstron. The strong nearby sources that may be searched and their observing status are:

NGC3079 - 3.5 Jy - masering material shocked ISM in nucleus - detected at 1.6 - 2.3 ED
NGC4258 - 9.8 Jy - maser regions in compact nuclear disk - detected at 1.4 - 26.7 ED
NGC4945 - 8.5 Jy - masers in nuclear disk - not yet searched
N133 and 30Dor - 70 & 3 Jy - star formation regions in LMC - not yet detected
Circinus - 4.2 Jy - masers in Keplerian disk & bi-conical outflow - not yet detected
IC133 - 1.5 Jy - star formation region in M33 - not yet searched
NGC1068 - 0.65 Jy - Keplerian nuclear disk - potential candidate

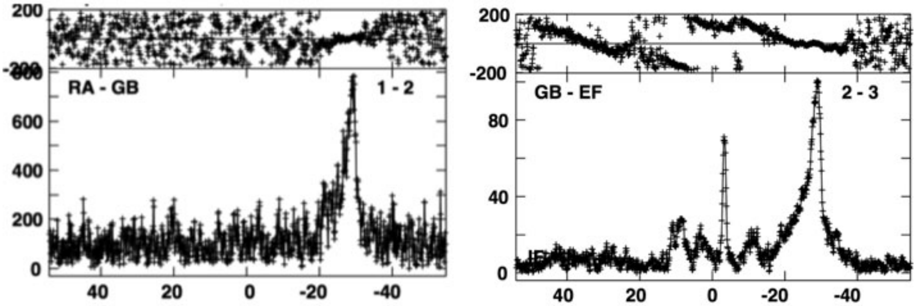

Figure 1. RadioAstron detection of NGC 3079 with Green Bank Telescope (GBT) at 2.3 ED. (left) The uncalibrated cross-correlation and fringe phase spectrum on the RAO-GBT baseline. (right) The uncalibrated cross spectrum and the fringe phase on the GBT - Effelsberg baseline. The axes are in arbitrary units of flux density and the velocity scale is centered at 984 km s^{-1}.

The initial detections of both NGC 3079 and NGC 4258 were obtained from observations in late 2014. After the update of the orbital elements for the ASC correlator (Likhachev *et al.* 2017), ten more new detections have been obtained for NGC 4258 up to a baseline of 26.7 Earth Diameters (ED).

2. NGC 3079 results

The high-brightness maser components in the H_2O MM NGC 3079 form an arc that is offset from the triple components of the Compact Symmetric Object (CSO) at the nuclear center (Kondratko, Greenhill and Moran 2005). The systemic velocity of NGC 3079 is 1116 km s^{-1} at a distance of 15.2 Mpc, while the main maser components are blueshifted between 950 - 990 km s^{-1}. Although initially the string of maser components has been interpreted as part of a rotating disk, the component velocities and the offset arc-structure do not support that picture. Instead, it appears that the maser components are a shocked part of the nuclear ISM that is also seen in blueshifted OH and HI components (Hagiwara, Klöckner and Baan 2004). These components are possibly connected to the two super-starburst regions found East of the core (Middelberg *et al.* 2007), which appear to be associated with the nuclear blowout seen in the optical. Shocks passing through the nuclear ISM provide for the H_2O population inversions resulting in the amplification of diffuse radio background across the nuclear region (see Baan and Irwin 1995), which in turn will result in concentrated regions of diffuse and compact emission.

The cross-correlation spectrum of NGC 3079 from the RAO-GBT observation at 2.3 ED has been presented in Figure 1a and shows two features peaking at 963 and 955 km s^{-1}. The strength of the features on the space-Earth baseline is significantly lower than obtained on the terrestrial baseline between GBT and Effelsberg in Figure 1b. The other features in the terrestrial spectrum were not detected on the space-Earth baseline and no detections have been made for NGC 3079 at any longer baselines.

The decrease in strength of the detected features and the fact that no further detections were made at longer baselines would indicate that the maser emission is mostly extended at a 2.3 ED baseline, and appears completely resolved at longer baselines. The beam size at 2.3 ED suggests that the strongest masering components in the nuclear medium are larger than 1400 AU at the distance of NGC 3079, which is consistent with amplification by diffuse medium. Although the association with shocks resulting from the super-starburst regions is not confirmed, any change in the velocity and spatial structure of the maser components found in past VLBI observations may help to confirm the nature of the excitation of these masering regions.

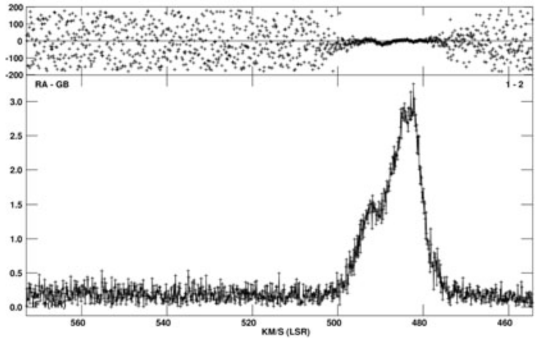

Figure 2. RadioAstron detection of NGC 4258. The uncalibrated cross-correlation spectrum of the RAO-GBT baseline of 1.9 ED. Flux density (arbitrary units) is plotted versus radial velocity.

3. NGC 4258 results

The H_2O MM emission regions in NGC 4258 are confined to a nearly edge-on disk of 0.5 pc surrounding the nuclear AGN (Herrnstein *et al.* 1998), also qualified as a CSO. The orbiting molecular regions within the disk drift in front of the southern part of the CSO radio continuum and amplify this continuum. Because of the orbital motion in the disk, the masering components drift across the spectrum from low velocity to high, at approximately 8.1 km s^{-1} yr^{-1} across the velocity range 440 - 550 km s^{-1} (Haschick, Baan and Peng 1994, Humphreys *et al.* 2008). The systemic velocity of NGC 4258 is 472 km s^{-1} at a distance of (approximately) 7 Mpc and at half the distance to NGC 3079.

At the time of this writing, the H_2O MM emission in NGC 4258 has been detected with 11 RadioAstron experiments, the first dating back to 2014. While fringes were initially found in observational data at a baseline of 1.9 ED, the updated orbital model of RAO at the ASC correlator resulted in subsequent detection of fringes up to baselines of 26.7 ED (corresponding to 340,000 km). The detection of fringes of the H_2O MM emission on this long RAO-GBT baseline constitutes an absolute record of 8 μas in angular resolution.

The RAO-GBT cross correlation spectrum for NGC 4258 at a baseline of 1.9 ED is presented in Figure 2. This (uncalibrated) spectrum shows a two-component profile that resembles the one obtained with terrestrial baselines, except for the lower amplitude on the space-Earth baseline. The resolution obtained for this baseline is 110 μas, which corresponds to 790 AU at the distance of NGC 4258. The profile also shows that a large fraction of the emission regions has not yet been resolved at this resolution, which is different from the results obtained for NGC 3079 at lower spatial resolution.

At higher resolution an increasing part of the diffuse maser components in NGC 4258 will be resolved, and only more compact components will remain unresolved. This is evident in the fringe amplitude plot of the detection with the 26.7 ED RAO-Medicina baseline displayed in Figure 3. Three individual components may be identified in this plot with a spatial resolution of 56 AU at the distance of NGC 4258. The mere detection of such compact masering components in NGC 4258 provides stringent limits on the degree of saturation and the excitation process. In addition, these more compact masering regions are likely to have less tangled magnetic fields and may allow detection of the magnetic field strength by its polarization properties.

4. Overview

The RadioAstron space-VLBI mission has successfully detected extragalactic H_2O MegaMaser emission regions, at space-Earth baselines ranging from 1.4 to 26.7 ED. The

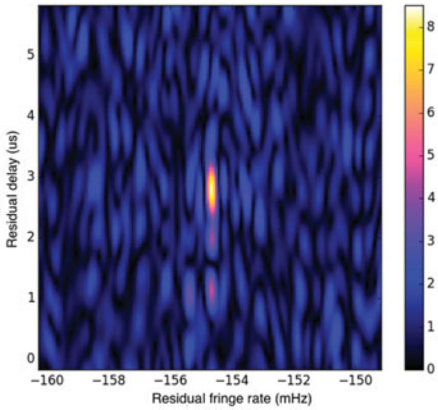

Figure 3. The fringe amplitude plot of the RAO-Medicina detection of NGC 4258 at 26.7 ED. The ratio of the interferometer fringe amplitude to the average noise amplitude is plotted against residual delay and fringe rate.

preliminary results for NGC 3079 and NGC 4258 at shorter baselines already indicate masering environments and excitation conditions that are distinctly different for the two galaxies. Although NGC 3079 has not been detected at baselines longer than 2.3 ED, early results for NGC 4258 suggest that individual masering regions can be detected at longer baselines up to 340,000 km.

5. Acknowledgements

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