

Water Vapour Maser Emission in the Type 2 Seyfert galaxy NGC 1068

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Abstract

Observations of 22 GHz water maser emission in the Type II Seyfert galaxy NGC 1068 using the Multi-Element Radio Linked Interferometer Network (MERLIN) are presented in this article. Two-epochs of MERLIN observations were conducted at about $0''.02$ angular resolution by covering the velocity range of Doppler-shifted H₂O maser emission. I report the result of the spectral-line observations of H₂O maser associated with the radio jet offset from the radio nucleus of the galaxy. The maser emission at the off-nuclear jet component in the galaxy was not detected in the new observations, which might be due to intensity variability of the maser or the fact that the maser is resolved out by the synthesized beam that is about factors of 3-5 smaller than that in the earlier Very Large Array observations. The maser features lying at $V_{\text{LSR}} = 850 - 1150 \text{ km s}^{-1}$ were detected, most of them were found at near the radio nucleus of the galaxy. These masers remain unresolved at the synthesized beam of $0''.02$, or ~ 1.4 parsecs. I interpret these maser features being the blue-shifted emission that is a part of a rotating disk proved in the nucleus of NGC 1068 by earlier studies with milliarcsecond resolution using VLBI. Further observations are required in order to detect and resolve the off-nuclear maser as well as the nuclear H₂O maser in the galaxy.

keywords: interstellar medium, molecular gas, maser, active galaxies

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1 Introduction

Astronomical maser (Microwave Amplification by Stimulated Emission of Radiation) naturally occurs in the sites of star-formation and evolved stars in our Galaxy, and also in extragalactic objects under peculiar physical conditions. Molecular gas such as hydroxyl (OH), methanol (CH₃OH), and water (H₂O) emits intense maser radiation in the interstellar space. OH and H₂O masers are observed also in distant extragalactic sources. Some of these extragalactic masers have large radiation luminosity compared with those in our Galaxy and are called *megamaser*.

It is known that H₂O masers in the transition of 6₁₆ – 5₂₃ at 22.23508 GHz ($\lambda = 1.35$ cm) observed commonly in Galactic objects exist in the central regions of active galaxies, most of which are H₂O megamasers. Some fraction of the H₂O megamasers are called "nuclear masers" that are associated with activity of active galactic nuclei (AGN). The nuclear masers have proved themselves being powerful in tracing angular geometry in central few parsecs (pc) from central engine of AGN (e.g., Moran et al. 1999). More than 150 extragalactic H₂O masers have been discovered to date, most of which are detected exclusively towards narrow-line AGN (e.g., Braatz et al. 2003). Observations of nuclear H₂O masers towards narrow-line active galaxies such as Type 2 or narrow-line Type 1 Seyferts (Hagiwara et al. 2003; Hagiwara et al., in preparation) and LINERs are a unique tool for studying kinematics of central sub-parsecs of AGN. It should be noted that extragalactic H₂O masers in AGN are detected at sub-millimeter wavelengths, however it is uncertain that these masers probe the central parsecs of AGN as well as the 22 GHz masers (Humphreys et al. 2005; Hagiwara et al. 2013).

A bright H₂O maser emission (see Fig. 1) is known towards the nuclear region of a narrow-line Type 2 Seyfert galaxy, NGC 1068 (e.g., Gallimore et al. 2001). The nucleus of NGC 1068 harbors the prototypical example of an AGN obscured by molecular materials surrounding a central engine of the galaxy in line of sight. VLBI (Very Long Baseline Interferometer) observations revealed that the nuclear masers in NGC 1068 (D=14.4 Mpc; Tully and Fisher 1988, 1" = 72.0 pc) are distributed linearly extending from the red-shifted to blue-shifted velocity at $V_{\text{LSR}} = \sim 800 - 1500 \text{ km s}^{-1}$ (Greenhill et al. 1996, 1997). The extension of these masers indicates the presence of an edge-on ($i > 80^\circ$) thin disk in the center of the galaxy. Gallimore et al. (1996a) reported the detection of H₂O maser towards a radio jet component C at a mid-point between two major components displayed in Fig.2, which locates about 0.3 arcsecond north of the nucleus S1 (southern component in Fig.2) using the Very Large Array (VLA). The maser at the component C is blue-shifted $\sim 150 \text{ km s}^{-1}$ with respect to the galaxy's systemic velocity of $V_{\text{LSR}} = 1150 \text{ km s}^{-1}$ (Gallimore et al. 1996a,b). It is understood that this "off-nuclear" maser in the galaxy traces shocked dense molecular gas at component C where the jet -interstellar medium (ISM) interaction occurred in the environment of ambient molecular materials (Gallimore et al. 1996). These H₂O maser features associated with the radio jet component would provide critical information to study

circumnuclear environment of AGN when combined with those found in a disk around the central engine. The nature of the off-nuclear maser in the galaxy has been under debate. Thus, it seems to be important to follow up the earlier study with higher angular resolution for clarifying the origins of the maser in terms of radio imaging.

In this article, new observation of the "off-nuclear" maser in NGC 1068 is presented. This may enable to interpret overall properties of H₂O masers in the galaxy, as well as the shock front between ISM and a radio jet.

2 Observation

Spectral-line observations at 22 GHz with the five telescopes of Multi-Element Radio-Linked Interferometer Network (MERLIN)* in UK, including the Mark 2 telescope were performed for measurement of the $6_{16}-5_{23}$ transition of H₂O maser emission toward NGC 1068. The observations of NGC 1068 were carried out over periods of 6-7 April in 2002 for ~ 16 hours in total. Phase-tracking position for NGC 1068 was RA 02^h42^m40^s.711, Dec. -00°00'47"810 (J2000). In these observations, a single IF band of width 16 MHz with opposite circular polarizations divided into 64 spectral channels, yielding velocity resolutions of 250 kHz (3.37 km s⁻¹) was centered at the one frequency setting and changed to other two frequency settings by shifting center frequency during observations. By doing this, we obtained three IF center frequencies, centered at $V_{\text{LSR}} = 597, 899, \text{ and } 1092$ km s⁻¹. The resultant velocity coverage was $V_{\text{LSR}} = 502-699$ km s⁻¹ and $V_{\text{LSR}} = 801-1189$ km s⁻¹. The velocity range $V_{\text{LSR}} = 700-800$ km s⁻¹ was not observed. Phase-referencing observations were conducted at each frequency set, using the calibrator source 0237-027 (RA 02^h39^m45^s.4723, Dec. -02°34'40"913 (J2000)). The phase-referencing observations were executed in a sequence of 6 min scans with cycling interval of 250 sec for NGC 1068 and 70 sec for 0237-027.

Amplitude and bandpass calibration was performed by observations of 3C 286 and 3C 273, respectively.

The synthesized beam size produced from spectral-line data was $0.043'' \times 0.021''$ in the position angle of 57°. The rms noise level per a single spectral channel ($\Delta\nu = 250$ kHz) was about 5.8 mJy beam⁻¹, typically.

3 Results and discussion

3.1 Off-nuclear maser emission

The maser in the nuclear region of the galaxy was searched in the velocity range of $V_{\text{LSR}} = 800 - 1189$ km s⁻¹, within 0.768×0.768 arcsec² area, centered on the phase

*MERLIN is operated by the University of Manchester as a National Facility of the Science and Technology Facilities Council (STFC), and is available for use on a peer-review basis, with observing proposals dealt with by the Panel for Allocation of Telescope Time (PATT). The National Facility also hosts Jodrell Bank Observatory's VLBI participation, linking telescopes across Europe.

tracking center of the MERLIN observations, however no maser at the off-nucleus jet component C in the galaxy was detected in a 3σ value of ~ 17 mJy. Non-detection of the off-nuclear maser might be due to intensity variability of the maser or the fact that the maser is resolved by the synthesized beam that is the factor of about 3-5 smaller than that in the earlier Very Large Array (VLA) observations. The latter case is less likely since the detection of the nuclear maser lying near the systemic and red-shifted velocity range using VLBI at sub-milliarcsec angular resolution has been reported (Greenhill et al. 1996). The maser at radio jet component C was previously detected around at velocities between 1000 and 1200 km s⁻¹ by the VLA in 1987, and the flux density of the maser was ≈ 50 mJy (Gallimore et al. 1996a). If the maser intensity remained as strong as it was in 1987, it should have been seen in our observation. Accordingly, it is likely that the strength of the maser had become weaker than that in 1987 when the VLA measurement was executed. Further observation with better imaging sensitivities would be necessary to detect and pin-point the location of the off-nuclear maser.

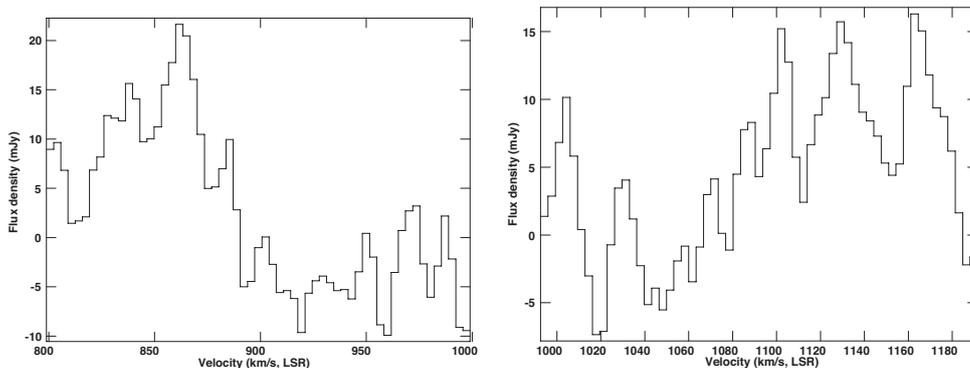


Fig. 1: Spectra of 22 GHz H₂O maser emission spanning from $V_{\text{LSR}} \approx 800$ -1200 km s⁻¹ towards the radio nucleus (S1) of the Type 2 Seyfert galaxy NGC 1068, obtained by the MERLIN on 6-7 April 2002.

3.2 Nuclear maser emission

The radio nuclear structure of NGC 1068 constitutes of several radio sources in which there are four major components of NE, C, S1, and S2 (Gallimore et al. 1996a, 1996b, 1997; Muxlow et al. 1996), among which the source S1 that 22 GHz VLBI observations failed to image is recognized as a central engine of the galaxy because of its resolved structure showing an inverted spectrum and a relatively flat spectral index, $\alpha \sim +0.3$, where $S_\nu \propto \nu^\alpha$, with S_ν being the flux density at frequency ν , at centimeter wavelengths (Muxlow et al. 1996, Gallimore et al. 1997, 2004).

The nuclear maser features of NGC 1068 spanning from $V_{\text{LSR}} = 870 - 1030$ km s⁻¹ were detected (see Fig.1), most of them are found at near the Seyfert nucleus of the galaxy. These masers remain unresolved within the synthesized beam size of 0.02 arcsecond

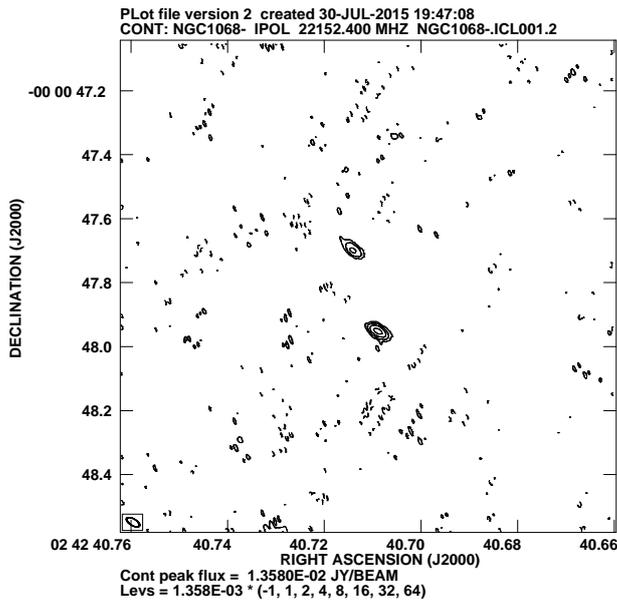


Fig. 2: A model-fitted image of 22 GHz radio continuum components in the nuclear region of NGC 1068 is displayed. The 22 GHz H₂O maser emission is found towards the southern radio component in the image.

(Fig.3), that is about 1.4 pc at the distance of the galaxy. The position of the maser at $V_{\text{LSR}} = 1162.8 \text{ km s}^{-1}$ is RA $02^{\text{h}}42^{\text{m}}40^{\text{s}}.7091$, Dec. $-00^{\circ}00'47''.9479$ (J2000). The position is coincident with that of the radio continuum nucleus S1 at the MERLIN synthesized beam. The fact that the maser emission was not resolved with the MERLIN synthesized beam is consistent with the earlier studies in which the distribution of the maser spots in the galaxy was imaged at milliarcsec resolution with VLBI (Greenhill et al. 1996). In our measurements, the detected maser is blue-shifted up to about 300 km s^{-1} from the systemic velocity of the galaxy ($V_{\text{LSR}} = 1150 \text{ km s}^{-1}$). Milliarcsec VLBI imaging of the red-shifted maser emission lying from $V_{\text{LSR}} \approx 1100 - 1500 \text{ km s}^{-1}$ revealed that the red-shifted emission extends roughly 0.6 pc to north-west from the center and traces an edge-on disk (Greenhill et al. 1996), while the blue-shifted emission linearly extends roughly north to south and shows velocity gradient in the reverse direction of that of the red-shifted maser (Greenhill et al. 1997). I interpret the blue-shifted maser features measured in our observation being as part of the blue-shifted maser that proved to be on the disk in the nucleus of NGC 1068 with VLBI.

It should be also remarked that the radio nuclear continuum emission was not detected to a 3σ rms noise $\sim 2 \text{ mJy beam}^{-1}$ on the NGC 1068 image. A model-fitted map of NGC 1068 is presented in Fig.2. The location between the maser and the 22 GHz nuclear continuum has not been detected in earlier observations.

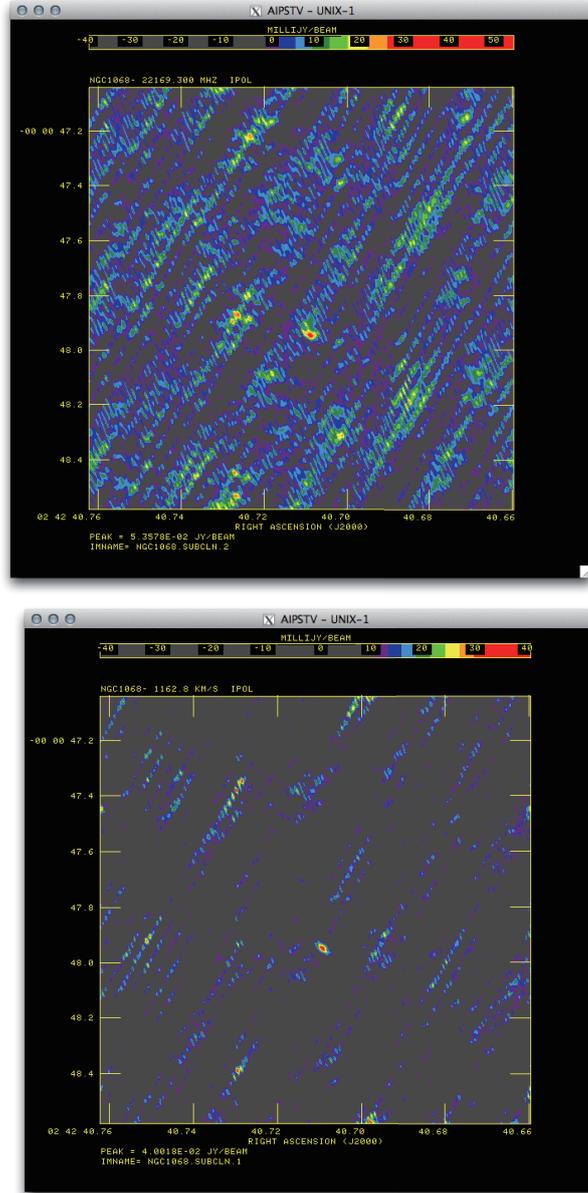


Fig. 3: False color images of 22 GHz H₂O maser emission lying at $V_{\text{LSR}} = 865.1 \text{ km s}^{-1}$ (*upper*) and 1162.8 km s^{-1} (*lower*) in NGC 1068, obtained using the UK radio interferometer MERLIN. The compact maser emission is seen near the center in each panel. Intensity of the maser is scaled in milli Janskies (mJy) by a horizontal bar, where 1 mJy corresponds to $10^{-26} \text{ erg}^{-1} \text{ Hz}^{-1} \text{ cm}^{-2}$.

3.3 Future work

The early-time MERLIN has been renewed to e-MERLIN with the wider bandwidth up to 4 GHz, which resulted in upgraded continuum sensitivity down to $\sim 1 \mu\text{Jy}$ level. With the upgraded sensitivity of the current e-MERLIN, it might be possible to detect the off-nuclear maser since the improved continuum sensitivity would help in detecting the phase-referencing source with better sensitivity by factors of ~ 15 using the full bandwidth of 4 GHz, instead of 16 MHz in our observation in this article. Moreover, this would contribute in detecting the nuclear continuum sources in NGC 1068 at 10 milliarcsec resolution, which enables to register the location of the maser and the continuum structure at 22 GHz.

4 Summary

Non-detection of the off-nuclear H_2O maser in NGC 1068 performed at the highest angular resolution of $0.02''$ using the MERLIN might be due to variability of the strength of the maser or the fact that the maser was resolved out. The latter is less likely because the angular size of a maser spot should be smaller than the synthesized beam size of our observation. However, the interpretation of non-detection of the off-nuclear maser in the galaxy is not straightforward. We detected a part of the blue-shifted maser emission towards the radio nucleus S1, however the angular distribution of the maser was not revealed due to the lack of angular resolution. The location of the detected maser emission is confined within the synthesized beam size and the detection constrained the location of the maser in the nuclear region, which indicates the presence of dense molecular gas or a maser disk within ~ 1 pc from the central engine. Follow-up observations using the upgraded e-MERLIN having wider receiving bandwidths would be able to reveal the nature of the off-nuclear maser.

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和文概要

2型セイファート銀河 NGC 1068 中の水蒸気メーザー

萩原喜昭

要旨

2型セイファート銀河 NGC 1068 中にある水蒸気メーザーの観測的研究に関して報告する。