# 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 2 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 $H_2O$ maser emission. I report the result of the spectral-line observations of $H_2O$ 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 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 $V_{LSR}$= 850–1150 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 $H_2O$ maser in the galaxy.

**Keywords**：interstellar medium, molecular gas, maser, active galaxies

## 1 Introduction

Astronomical maser (Microwave Amplification by Stimulated Emission of Radiation) naturally occurs in the sites of starformation and evolved stars in our Galaxy, and also in extragalactic objects under peculiar physical conditions. Molecular gas such as hydroxyl (OH), methanol ($CH_3OH$), and water ($H_2O$) emits intense maser radiation in the interstellar space. OH and $H_2O$ masers are observed also in distant extragalactic sources. Some of these extragalactic masers have large radiation luminosity compared

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with those in our Galaxy and are known as *megamaser*.
It is known that $H_2O$ masers in the transition of $6_{16}$–$5_{23}$ 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 $H_2O$ megamasers. Some fraction of the $H_2O$ megamasers are called "nuclear masers" that are associated with the activities 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 $H_2O$ masers have been discovered to date, most of which are detected exclusively toward narrow-line AGN (e.g., Braatz et al. 2003). Observations of nuclear $H_2O$ masers toward 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 the kinematics of central sub-parsecs of AGN. It should be noted that extragalactic $H_2O$ masers in AGN are detected at sub-millimeter wavelength, 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 $H_2O$ maser emission (see Fig. 1) is known toward 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 $V_{LSR}$= ~ 800 – 1500 km $s^{-1}$ (Greenhill et al. 1996, 1997). The extension of these masers indicates the presence of an edge-on ($i$ > 80°) thin disk in the center of the galaxy. Gallimore et al. (1996a) reported the detection of $H_2O$ maser toward 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 ~150 km $s^{-1}$ with respect to the galaxy's systemic velocity of $V_{LSR}$= 1150 km $s^{-1}$ (Gallimore et al. 1996a,b). It is understood that the "off-nuclear" maser in the galaxy traces shocked dense molecular gas at the component C where the jet-interstellar medium (ISM) interaction occurred in the environment of ambient molecular materials (Gallimore et al. 1996). These $H_2O$ maser features associated with the radio jet component would provide crucial 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 studies with higher angular resolution for clarifying the origins of the maser in terms of radio imaging.

In this article, the new observations of the "off-nuclear" maser in NGC 1068 are presented. This may enable to interpret overall properties of $H_2O$ 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 $H_2O$ 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 $V_{LSR}$= 597, 899, and 1092 km $s^{-1}$. The resultant velocity coverage was $V_{LSR}$= 502-699 km $s^{-1}$ and $V_{LSR}$= 801-1189 km $s^{-1}$. The velocity range $V_{LSR}$= 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 were 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.

*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.

# 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 $V_{LSR}$= 800–1189 km $s^{-1}$, within 0.768 × 0.768 $arcsec^2$ area, centered on the phase tracking center of the MERLIN observations; however, no maser at the off-nuclear jet component C in the galaxy was detected in a $3\sigma$ 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 the 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.

## 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

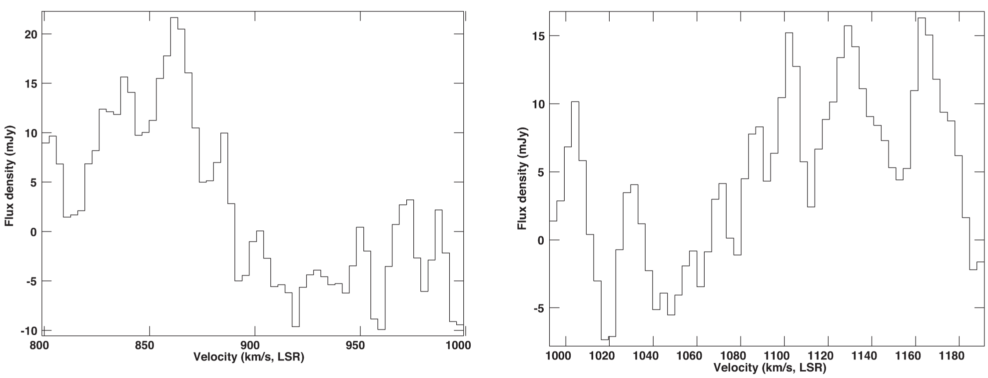


**Fig. 1** : Spectra of 22 GHz $H_2O$ mater emission spanning from $V_{LSR}$≈ 800-1200 km $s^{-1}$ toward the radio nucleus (S1) of the Type 2 Seyfert galaxy NGC 1068, obtained by the MERLIN on 6-7 April 2002.

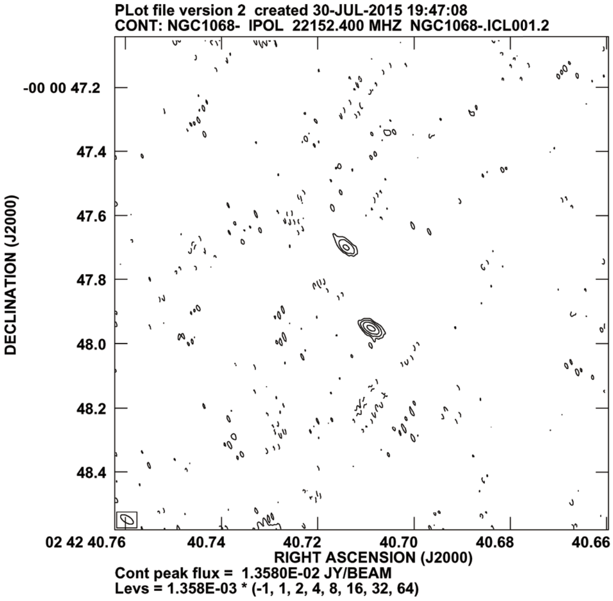


**Fig. 2**：A model-fitted image of 22 GHz radio continuum components in the nuclear region of NGC 1068 is displayed. The 22 GHz $H_2O$ maser emission is found toward the southern radio component on the image.

structure showing an inverted spectrum and a relatively flat spectral index, $\alpha \sim +0.3$, where $S_\nu \propto \nu^\alpha$, with $S_\nu$ being the flux density at frequency $\nu$, at centimeter wavelength (Muxlow et al. 1996, Gallimore et al. 1997, 2004).

The nuclear maser features of NGC 1068 spanning from $V_{LSR}$= 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. 3), that is about 1.4 pc at the distance of the galaxy. The position of the maser at $V_{LSR}$= 1162.8 km $s^{-1}$ is RA $02^h42^m40^s.7091$, Dec. -00°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 ($V_{LSR}$= 1150 km $s^{-1}$). Milliarcsec VLBI imaging of the red-shifted maser emission lying from $V_{LSR} \approx$ 1100–1500 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

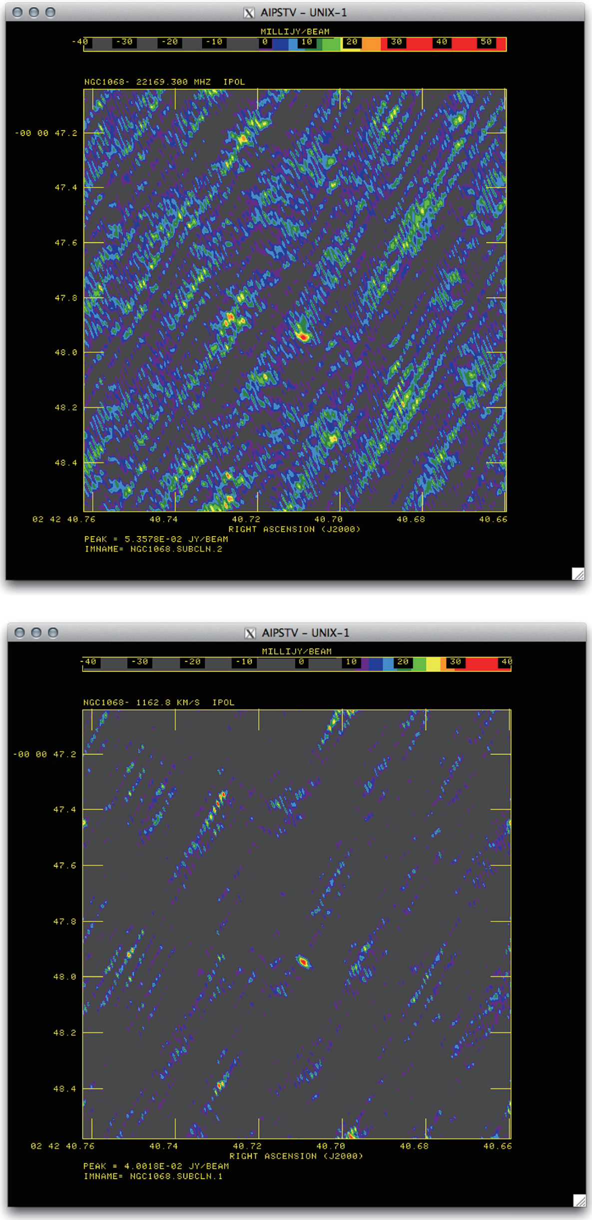


**Fig. 3**: False color images of 22 GHz $H_2O$ maser emission lying at $V_{LSR}$=865.1 km $s^{-1}$ (*upper*) and 1162.8 km $s^{-1}$ (*lower*) in NGC 1068, obtained using the UK radio interferometer MERLIN. The compact maser emission is seen near the center in each panel. Intensity of the maser is scaled in milli Janskies (mJy) by a horizontal bar, where 1 Jy corresponds to $10^{-26}$ $erg^{-1}$ $Hz^{-1}$ $cm^{-2}$ .

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 $3\sigma$ rms noise ~2mJy beam$^{-1}$ on the NGC 1068 image. A model-fitted map of NGC 1068 is presented in Fig. 2. The relative location of the maser and the 22 GHz nuclear continuum has not been registered in earlier observations.

### 3.3 Future work

The early-time MERLIN has been renewaled to e-MERLIN with the wider bandwidth up to 4 GHz, which resulted in upgraded continuum sensitivity down to ~ 1 $\mu$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, that 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 toward 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 and the new receiver 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

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## 要旨

２型セイファート銀河であるNGC 1068の中心核付近には、明るい22GHz帯の水蒸気メーザーが存在する。一方、同銀河の中心核から噴出した電波ジェットが周囲の物質と衝突してくびれた位置にもメーザーが存在することが知られる。本研究では、高空間分解能での電波観測により、ジェットによるショックで励起されたメーザーの空間分布と運動学を調べることを目的とした。解析の結果、中心エンジン近傍に分布するメーザーの検出はできたが、ジェット付近のメーザーは検出されなかった。未検出の原因は、メーザーの強度変動によるものか、あるいはメーザーが空間的に分解されたか、であると結論した。