Cosmic Masers: Proper Motion toward the Next-Generation Large Projects
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Water masers associated with AGN in radio galaxies

Satoko Sawada-Satoh

Osaka Metropolitan University, Sakai-shi, Osaka 599-8531, Japan. email: swdsth@gmail.com

Abstract. We present dual-frequency VLBI observations of a nearby radio galaxy NGC 4261 at 22 and 43 GHz using the East Asia VLBI Network. In particular, the first sub-pc scale image of the 22 GHz water megamaser line in the circumnuclear region of NGC 4261 is shown. Our results suggest that the megamaser emission in NGC 4261 can be associated with the inner radius of the obscuring disk, as it is proposed for the nearest radio-loud megamaser source NGC 1052. An alternative hypothesis on the megamaser association is the shock region of the interaction between the jet and ambient molecular clouds.

Keywords. galaxies: active, galaxies: nuclei, radio lines: galaxies

1. Introduction

22 GHz water megamasers have been explained as a possible signature of AGN phenomena such as acccretion disk (e.g. NGC 4258) and nuclear outflow (e.g. Circinus). They are mostly associated with radio-quiet AGNs. Water megamasers have been found in a limited number of radio-loud AGNs such as NGC 1052 (Braatz *et al.* 1994; Claussen *et al.* 1998), TXS 2226-184 (Koekemoer *et al.* 1995; Surcis *et al.* 2020), 3C 403 (Tarchi *et al.* 2003, 2007), Mrk 348 (Peck *et al.* 2003) and NGC 4261 (Wagner 2013). Past multi-frequency VLBI observations of the nearest radio-loud water megamaser NGC 1052 have proposed a model that maser clouds in the radio galaxy NGC 1052 lie in a circumnuclear torus, and amplify the continuum seed emission from the jet knots in the background (Sawada-Satoh *et al.* 2008). However, the origin and excitation mechanism of water megamasers in radio-loud AGN still remains unclear to date. Therefore, determining the location and kinematics of water maser gas in the second-nearest radio-loud water megamaser source NGC 4261 is essential.

2. Water megamaser emission in NGC 4261

NGC 4261 is a nearby radio galaxy with a symmetric two-sided radio jet along the east-west direction. The western and eastern jet approach and recede from the observers, respectively (Haga *et al.* 2015). This galaxy is known to have a pc-scale obscuring disk or torus traced by ionized gas (Jones & Wehrle 1997; Jones *et al.* 2000) and neutral atomic hydrogen (van Langevelde *et al.* 2000) surrounding the central source.

Our VLBI observations marginally detected water megamaser line with a peak flux density of 12.9 mJy at 2289 km s^{-1}, slightly redshifted relative to the $V_{\rm sys}$ (Sawada-Satoh *et al.* 2023). Imaged velocity-integrated intensities (moment 0) maps reveal a prominent elongated structure, just east of the continuum peak position at 22 GHz (figure 1ac), where the free-free absorption opacity due to the ionized gas was high on the eastern receding jet. This suggests that the water maser gas spatially coincides with the ionized gas. The inner surface of the disk is directly illuminated with by

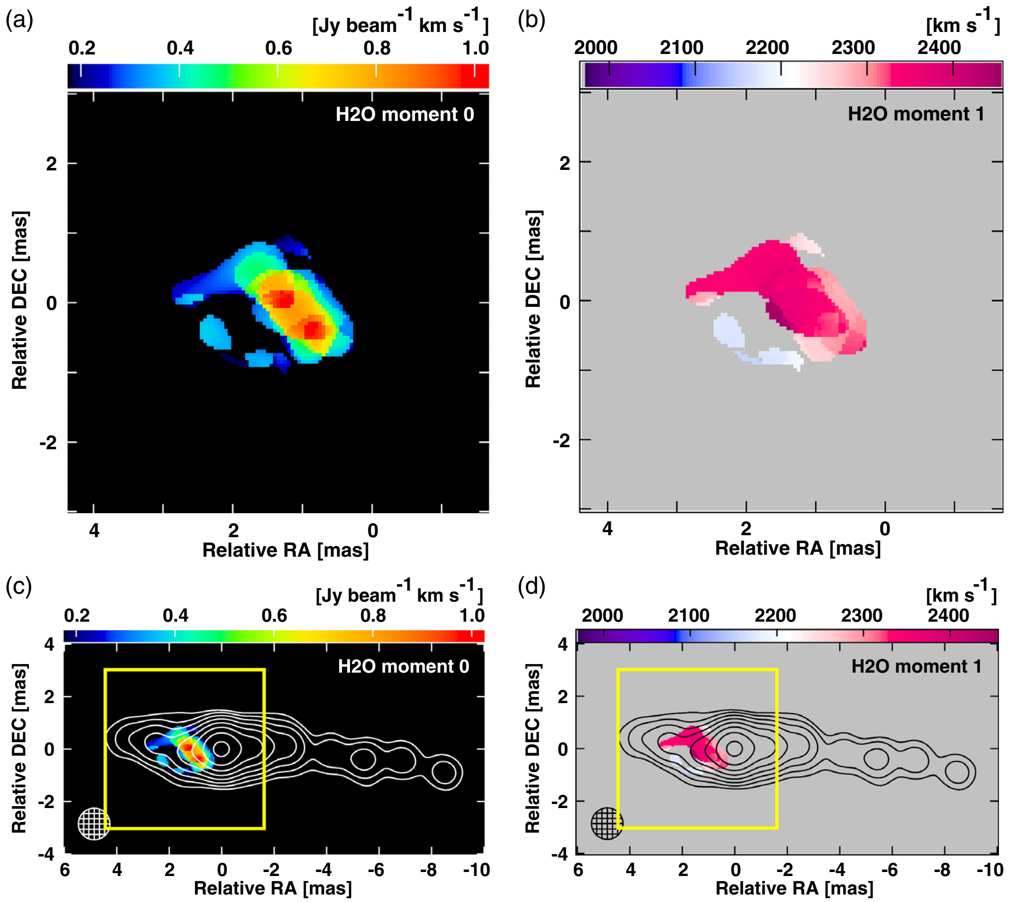

Figure 1. Close-up view of the (a) moment 0 and (b) moment 1 maps of the water megamaser. Relative distributions of (c) the moment-0 and (d) moment-1 maps with respect to the 22 GHz continuum image (Sawada-Satoh *et al.* 2023).

X-ray radiation from the central source, and an ionized gas layer is formed on the surface. Excited water molecular gas inside the near side of disk amplify the background continuum seed emission from the receding jet, and produce the luminous water megamaser emission. Intensity-weighted velocity (moment 1) maps show that the redshifted emission arises from the elongated structure (figure 1bd). The redshifted velocity could be ongoing infall motion from the disk toward the center. This is analogous to the multi-phase circumnuclear torus model in the nearest radio-loud water megamaser source NGC 1052 (Sawada-Satoh *et al.* 2008). Further high-sensitivity VLBI imaging would be helpful in better understanding the complex gas kinematics in the immediate vicinity of the SMBH.

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Review talk in the session Black Hole Masses and the M-sigma Relation by Masatoshi Imanishi. Taken by Ka-Yiu Shum.

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