Multiphase Gas Morphology and Dynamics in the Circumnuclear Region

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Abstract

Multiphase gas morphology and dynamics in the circumnuclear region of galaxies provide important clues for understanding the mechanism how active galactic nuclei (AGN) are fueled and release large mounts of energy to affect their environment. Circumnuclear kinematics has been traced by a mixture of different gas phases ranging from cold molecular gas to neutral atomic gas to hot ionized gas. Despite a growing number of circumnuclear gas studies, we still lack a clear consensus what trigger the gas inflowing toward a central supermassive black hole (SMBH) and subsequent feedback to host galaxy. The next generation Very Large Array will provide further insights into the mass accretion and feedback processes, optimizing its broad frequency coverage from 1.2 to116 GHz, wide range of angular resolution spanning from 1000 to 0.1 milliarcsecond, and extremely high sensitivity. In addition, the combination of high angular observations with other facilities will offer new opportunities for ultimate understanding the complex circumnuclear gas morphology and dynamics.

Key words: galaxies: active — galaxies: nuclei

1. Introduction

It is generally proposed that the highly energetic activity of AGN is powered by mass accretion onto a SMBH (Antonucci 1993). Accretion mass toward the center of galaxies fuels the SMBH, and the gravitational energy of accretion mass is turned into radiation, winds and jets. Those AGN mechanical energy releases can play a significant role in the evolution of its host galaxy (e.g., Croton et al. 2006; Sijacki et al. 2007). Morphology and dynamics of the circumnuclear gas in galaxies can set some constraints on the processes of AGN fueling and feedback.

Mass accretion in active galaxies that host gas-rich circumnuclear environment is considered to be triggered by circumnuclear star formation and supernova explosions (e.g., Kawakatu & Wada 2008; Izumi et al. 2016). On the other hand, it remains unclear whether such a process is also working properly in radio galaxies where circumnuclear star formation is inactive.

2. Dynamics on handreds-parsec scales

Interferometric observations towards nearby AGNs on handreds-parsec scales have unveiled circumnuclear gas dynamics, including inflow, outflow and rotation in last three decade. High angular resolution imagings of neutral atomic hydrogen (H I) 21 cm line in Seyfert galaxies show that H I absorbing gas could trace 100 parsec-scale rotation surrounding the center, which imply a circumnuclear disk (CND) (e.g., Gallimore et al. 1999). The H I lines can be observed at wider velocity range, which could be associated with the inflow and outflow motions from the center of radio galaxies (e.g., van Gorkom et al. 1989; Morganti et al. 1998). Those motions have been traced by a different type of physical phases not only ionized and atomic gas but also molecular gas. Multiphase gas observations have often reported that outflowing/inflowing gas and rotations gas can coexist on the scale of 10–100 parsec (e.g., Ott et al. 2001).

To illustrate what has been found in the multiphase gas dynamics, we show here the results for several example AGNs. One well-studied example is NGC 1275, a bright nearby radio galaxy. Inverted radio continuum spectra on the nuclear counterpart jet of this galaxy is explained as free-free absorption (FFA) by dense ionized gas which forms a disk structure (Vermeulen et al. 1994; Levinson et al. 1995). Velocity structure of molecular gas in the core of NGC 1275 also support the hypothesis of a rotation disk (Inoue et al. 1996; Wilman et al. 2005). Recent molecular line observations with the Atacama Large Millimeter/Submillimeter Array (ALMA) also suggest the presence of rotating and outflowing gases within 100 parsec in NGC 1275 (Nagai et al. 2019).

In the case of the nearby Seyfert 2 galaxy NGC 1068, the circumnuclear disk and outlow are probed by the various molecular emission lines such as CO, HCN, HCO^+, and CS (e.g., García-Burillo et al. 2014). Multi-line observations have shown the significant difference in molecular line ratios or chemical condition between the CND and the galactic disk (Viti et al. 2014). Further high angular resolution studies of multiple molecular lines with the Very Long Baseline Array (VLBA) and the ALMA reveal complex gas dynamics, including rotation, counter-rotation and outflow within central 100 parsec (e.g., Gallimore et al. 2004; Impellizzeri et al. 2019; Imanishi et al. 2020). Highly dynamical properties of circumnuclear multiphase gas is also presented in the nearest Seyfert 2 galaxy Circinus, through the collaboration of observational and theoretical studies (Wada et al. 2018a; Izumi et al. 2018; Wada et al. 2018b).

In addition, the combination of H I interferometric data and high resolution optical images by the Hubble Space Telescope has proposed a multiphase circumnuclear disk with atomic hydrogen gas at inner radius and dust at outer radius in the nearby radio galaxy NGC 4261 (Ferrarese et al. 1996; van Langevelde et al. 2000).

3. Dynamics on parsec/subparsec scales

One milliarcsecond angular resolution is required to unveil the parsec/subparsec-scale gas morphology and dynamics inside the CND of nearby AGNs with up to ~ 100 Mpc of distance. While conventional millimeter interferometer, even the ALMA long baselines, did not achieve such a high angular resolution, very long baseline interferometry (VLBI) has offered one milliarcsecond resolution. Compared to the case of multiphase gas studies on handred-parsec scales, gas tracers in parsec/subparsec-scale region are not many, because thermal emissions are not luminous enough to detect with the VLBI in general. Thus, circumnuclear gas morphology and dynamics on 0.1–10 parsec scales have investigated by absorption such as FFA and H I absorption on the non-thermal synchrotron radiation or bright non-thermal maser emission from excited molecular gas.

Multi-frequency VLBI observations have revealed parsec-scale ionized gas torus which obscures the core or innermost counter jet of the radio galaxies (e.g., Taylor 1996; Jones & Wehrle 1997; Tingay & Murphy 2001). In some case of them, the torus is also traced by H I absorption (e.g., Peck & Taylor 2001; Struve & Conway 2010). H I absorption can also trace the inflow toward the central SMBH (e.g., Taylor et al. 1999). Very luminous extragalactic H_2O masers associated with AGN have interpreted as a possible signature of a accretion disk (e.g., Miyoshi et al. 1995; Herrnstein et al. 1999), radiative shocks from the nuclear jet (e.g., Peck et al. 2003) or nuclear outflows (e.g., Greenhill et al. 2003).

There is almost no report about AGN with H_2O maser clouds coexisting with ionized gas in a circumnuclear torus, except a nearby radio galaxy NGC 1052. The results of multiphase gas dynamics in NGC 1052 are summarized here. VLBI observations toward the center of NGC 1052 at multiple frequency bands have revealed the presence of a dense circumnuclear ionized torus which obscures the very center of the galaxy (Kameno et al. 2001; Kadler et al. 2004). Follow-up simultaneous multi-frequency VLBI observations indicate that the H_2O maser clouds are distributed where the FFA opacity is high in the circumnuclear torus (Sawada-Satoh et al. 2008). VLBA images of OH absorption (Impellizzeri et al. 2008) also indicate a similar distribution to that of FFA and a similar velocity to that of H_2O maser emission. Kameno et al. (2005) has proposed the idea that the circumnculear torus consists of ionized and molecular gas, depending on the physical properties inside the torus. The idea of the torus with coexistence of ionized and molecular gas is improved as a torus model with multiphase gas layers: a hot ionized gas layer at the innermost edge where FFA opacity is large, a warm molecular gas interlayer where the H_2O maser emissions arise, and a cooler molecular gas layer where HCN and HCO^+ molecular clumps lie (Fig. 1), from the Korean VLBI Network observations (Sawada-Satoh et al. 2016; Sawada-Satoh et al. 2019). The redshifted velocity profiles of H_2O, OH, HCN and HCO^+ lines with respect to the systemic velocity of the galaxy are likely indicative of ongoing gas infall motion onto the SMBH. Furthermore, ALMA observations have found that the unresolved continuum emission of NGC 1052 casts many molecular absorption features (CO, HCN, HCO^+, SO, SO_2, CS, CN and H_2O), which can arise in a molecular torus surrounding the SMBH (Kameno et al. 2020).

The innermost radius of circumnuclear torus has been unclear, because the exact distance of FFA ionized gas from the SMBH cannot be measured along the line of sight. The innermost ionized gas of the circumnuclear torus could be located close to the broad line region (BLR), where clouds are ionized by photons from the accretion disk around the SMBH. Recent near-infrared Very Large Telescope Interferometer (VLTI) instrument, GRAVITY, have spatially resolved the BLR in a bright quasar 3C273. The visibility phase is well fitted by a thick disk model in circular orbit smaller than 0.1 parsec with a rotation axis aligned with the radio jet direction of 3C273 (Gravity Collaboration et al. 2018). The structure of BLR is possibly a continuation of the parsec-scale circumnuclear torus represented by FFA.

4. Impact of ngVLA

The next generation Very Large Array (ngVLA) will have a great impact on studies of multiphase gas surrounding the circumnuclear region. It is designed to achieve various angular resolutions ranging from ~ 1000 to 0.1 milliarcsecond and superb sensitivity of μJy level simultaneously, utilizing its three fundamental subarrays and additional long baselines. By filling the baseline gap between current interferometer and VLBI, the ngVLA will allow us to explore the mass accretion process of nearby AGNs at various spatial scales from galactic disk, CND to circumnuclear torus.

To fully understand the accretion and feedback of the AGN, high angular resolution observations of multiple gas tracers are necessary to probe each phase of the gas in the circumnuclear region. The wide frequency coverage from 1.2 to 116 GHz bands of the ngVLA can include many important atomic and molecular transitions, which are the key to study physics and chemistry of the interstellar medium (ISM) in galaxies. The broad bandwidth of ngVLA (up to 20 GHz) will enable to carry out the multi-line observations effectively.

5. Synergies with other facilities

Multi-frequency observations with the ngVLA and ALMA will be highly synergistic with exploration of the ISM condition. The higher frequency bands of ALMA can observe the mid- and high-J molecular transitions, while the ngVLA will detect low-J lines. The combination of the ngVLA and ALMA observations will play an important role to constrain the physical condition including density and temperature in the circumnuclear ISM.

The coordinated observations of the ngVLA with existing VLBI networks will considerably broaden the science of parsec-scale circumnuclear gas, providing very long baselines with high sensitivities. Especially, the cooperation between the ngVLA and Square Kilometer Array (SKA), will boost sensitivity extremely. As the ngVLA and SKA both will be capable of detecting H I line in the atomic phase, the joint observation

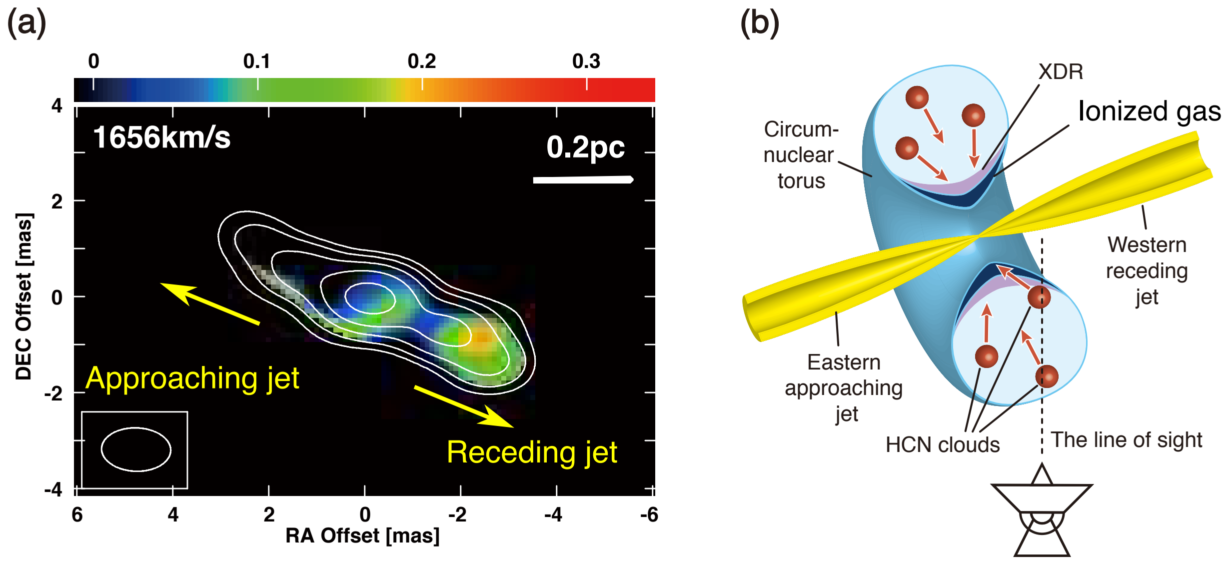

Fig. 1. (a) Subparsec-resolution image of the HCN optical depth at $V_{\rm LSR} = 1656$ km s^{-1} in the circumnuclear region of NGC 1052, overlaid by a contour map of double-sided radio continuum jet structure at 89 GHz. High optical depth is concentrated on the central nuclear and receding jet components, while no significant absorption is seen against the approaching jet. (b) Schematic picture for the intersection of the circumnuclear torus in NGC 1052. The torus consists of multiphase gas layers, hot ionized gas region on the innermost surface, warm excited molecular gas region at intermediate layer, and cooler molecular region at outer layer. Molecular layer is composed of gas clumps smaller than 0.1 parsec (See Sawada-Satoh et al. 2016).

of H I absorption using these arrays will be a powerful tool to make visible H I gas clumps in the circumnuclear region.

Finally, next-generation optical and infrared interferometers, such as VLTI, will provide complementary information about the photoionized gas in the vicinity of SMBH inside the circumnuclear torus.

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