Searching for intermediate-mass black holes in the Central Molecular Zone of our Galaxy

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Abstract

Intermediate-mass black holes (IMBHs) with masses of $\sim 10^2$–10^5 $M_\odot$ are key objects to reveal the origin of supermassive black holes and to understand galactic evolution. However, no definitive evidence of the existence of IMBHs has been obtained yet. Recently, we have discovered molecular gas streams suggesting the presence of IMBHs in the central region of our Galaxy. The high sensitivity and spatial resolution observations of the ngVLA will provide detailed kinematic information on such molecular clouds, enabling us to explore point-like radio sources corresponding to IMBHs. The ngVLA is a powerful instrument to search for the missing link of black holes.

Key words: Galaxy: center — ISM: clouds — ISM: kinematics and dynamics — ISM: molecules

1. Introduction

Most large galaxies are thought to harbor supermassive black holes (SMBHs) with masses of $\sim 10^6$–10^{10} $M_\odot$ at their centers. The observations of the S-stars around Sgr A* (e.g., Gravity Collaboration 2018) and the BH shadow in M87 (e.g., Event Horizon Telescope Collaboration 2019) have provided firm evidence for the existence of SMBHs. The discoveries of high-redshift quasars at $z > 7$ have indicated that SMBHs can be formed in less than a billion years after the Big Bang (e.g., Matsuoka et al. 2019).

The origin of SMBHs has been one of the key issues in astronomy and cosmology. SMBHs are hypothesized to grow through multiple merging and/or accretion of "seed" intermediate-mass BHs (IMBHs) with masses of $\sim 10^2$–10^5 $M_\odot$ (e.g., see Figure 1 in Mezcua 2017). Since not all IMBHs in the early universe should have grown into SMBHs, there are presumed to be leftover IMBHs in the local universe.

Many efforts have been made to confirm the existence of IMBHs so far (e.g., see the recent review by Greene et al. 2020). For example, several ultra-luminous X-ray sources have been considered as promising IMBH candidates (e.g., Matsumoto et al. 2001). Several globular clusters and dwarf galaxies have been suggested to harbor massive ($\sim 10^4$–10^5 $M_\odot$) IMBHs at their centers (e.g., Noyola et al. 2008). Nevertheless, these results have been still controversial, i.e., the existence of IMBHs has not been definitively corroborated yet. Finding IMBHs is essential for further understanding of the formation of SMBHs and galactic evolution.

2. Indications of IMBHs in the Galactic center

Massive objects tend to sink toward central regions of galaxies by dynamical friction. The Galactic center is one of the best regions to search for IMBHs because of its proximity. Within ~ 200 pc from the Galactic nucleus Sgr A*, there are huge amounts of warm and dense molecular gas as well as innumerable stars (e.g., Morris & Serabyn 1996). This region is referred to as the Central Molecular Zone (CMZ). Theoretical calculations have suggested that IMBHs may have been brought in the CMZ by infalling star clusters (Fujii et al. 2009; Arca-Sedda & Gualandris 2018). Such wandering IMBHs have potential to gravitationally interact with the ambient molecular gas.

In the large-scale molecular gas surveys of the CMZ using single-dish telescopes, we have discovered a population of compact ($d \lesssim 5$ pc) molecular clouds with extremely broad velocity widths ($\Delta V \gtrsim 50$ km s^{-1}), which are called high-velocity compact clouds (HVCCs; e.g., Oka et al. 1998; Tokuyama et al. 2019). Most HVCCs are associated with no counterparts in other wavelengths. The absences of apparent energy sources render it difficult to understand them. The origins of HVCCs have been discussed in case studies of several HVCCs so far. Interactions with supernova explosions (Oka et al. 1999; Yalinewich & Beniamini 2018) and cloud-cloud collisions (Tanaka et al. 2014; Tanaka 2018; Ravi et al. 2018) have been suggested as possible explanations for HVCCs. Besides these interpretations, we have proposed that some HVCCs may be the clouds that have been gravitationally accelerated by invisible massive objects such as IMBHs (Oka et al. 2016, 2017; Takekawa et al. 2019a, 2019b, 2020).

The most promising HVCC which possibly hosts an IMBH is HCN–0.009–0.044 (Takekawa et al. 2019a). The ALMA molecular line observations with an angular resolution of $\sim 1''$ revealed the detailed structure and internal motion of HCN–0.009–0.044. A ring-like structure (Balloon) appears at the center of the field of view and an elongated structure (Stream) lies on the southeast of the Balloon (Figure 1(a)). Figure 1(b)

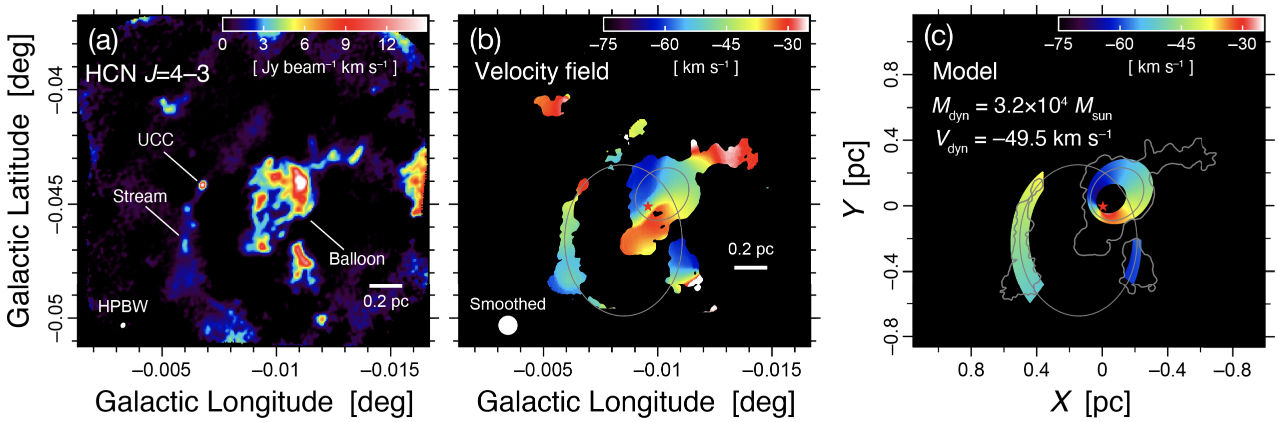

Fig. 1. (a) Integrated intensity map of HCN–0.009–0.044 in the HCN J=4–3 line obtained with the ALMA. (b) Moment-1 map of HCN–0.009–0.044 made by the HCN J=4–3 image smoothed with a 3$''$ FWHM Gaussian kernel. (c) Color map of the line-of-sight velocities of the modeled orbits with the best-fit values. The ellipses are the modeled orbits for the Balloon and Stream, respectively. The red star indicates the dynamical center.

shows the moment-1 map of HCN–0.009–0.044. The Balloon and Stream display clear velocity gradients: clockwise from the northern side to the south for the Balloon, and for the Stream, as it curves slightly from the southern side to the north. These velocity gradients can be naturally explained by orbital motions caused by gravity.

We found that the Balloon and Stream are moving probably along two different Keplerian orbits around a common single gravitational source through orbital fittings to the kinematic data. The mass ($M_{\rm dyn}$) and line-of-sight velocity ($V_{\rm dyn}$) of the dynamical center were derived as $M_{\rm dyn} = (3.2 \pm 0.6) \times 10^4$ $M_\odot$ and $V_{\rm dyn} = -49.5^{+1.0}_{-0.7}$ km s^{-1}. Figure 1(c) shows the reproduced velocity field with the best-fit parameters. These results strongly suggest that an enormous mass of 3×10^4 $M_\odot$ is packed within an area much smaller than 0.07 pc. Since no bright counterparts have been detected in this direction, it is quite likely that a massive IMBH with a very low accretion rate is lurking in HCN–0.009–0.044. This putative IMBH may be identified as a radio-continuum point source with the ngVLA.

3. Potential of the ngVLA to search for IMBHs

The ngVLA is expected to discover many Galactic stellar-mass BHs (Maccarone et al. 2018), IMBHs in globular clusters (Wrobel et al. 2018; Wrobel & Nyland 2020), and massive BHs with masses of $\gtrsim 10^5$ $M_\odot$ wandering around the outskirts of galaxies (Guo et al. 2020). We propose that HVCCs such as HCN–0.009–0.044 (Takekawa et al. 2019a), HCN–0.085–0.094 (Takekawa et al. 2020), CO–0.40–0.22 (Oka et al. 2016, 2017), and CO–0.31+0.11 (Takekawa et al. 2019b), are good candidates for ngVLA observations to search for point-like radio sources corresponding to IMBHs. The high sensitivity and spatial resolution of the ngVLA will enable us to detect a number of point sources toward HVCCs. The wide-band spectra are essential since non-thermal radio emission is expected to come from BHs. Radio-loud point sources could be effectively detected as IMBH candidates.

Radio variability is also an important clue to investigate the identity of the detected point sources. IMBHs could exhibit short-timescale radio variability like that of Sgr A*. The variability of Sgr A* at 43 and 22 GHz has been detected with a duration of ~ 2 hr (Yusef-Zadeh et al. 2006). Assuming a variability timescale of a BH is proportional to its mass, the variability timescale of an IMBH can be expected to be ~ 20 sec for $M_{\rm BH} = 10^4$ $M_\odot$ (or ~ 2 sec for $M_{\rm BH} = 10^3$ $M_\odot$) on the analogy of the flaring behavior of Sgr A*. Combining the observed spectra and variability with the kinematic information of the ambient gas, we may obtain more convincing evidence of the presence of IMBHs in HVCCs.

Molecular line observations at millimeter wavelengths (SiO J=2–1, CS J=2–1, etc.) are useful to trace kinematic structures of HVCCs in more detail. In our previous ALMA observations (Takekawa et al. 2019a, 2020), we have discovered several ultra-compact clumps with very broad velocity widths ($\Delta V \sim 50$ km s^{-1}). These clumps were not spatially resolved by the angular resolution of $\sim 1''$ (~ 0.04 pc at the Galactic center) and there are no counterparts in other wavelengths. Figure 2 shows one example of the clumps, which is also indicated as “UCC” in Figure 1(a). Such compact clumps are also good targets for the ngVLA observations. As is the case with HCN–0.009–0.044, the high-resolution molecular line observations ($\Delta\theta \lesssim 0.1''$) will potentially reveal the kinematics of the compact clumps. If the broad velocity width of each of the clumps is attributed to a Keplerian motion around a massive object in the CMZ, its orbital radius and rotational velocity is $R \lesssim 0.5''$ (~ 0.02 pc at the Galactic center) and $V_{\rm rot} \simeq 20$ km s^{-1}, respectively. The enclosed mass can be estimated to be $M_r \lesssim 10^3$ $M_\odot$ from these values. If the orbital radius is $R = 0.1''$, the enclosed mass is $M_r \sim 200$ $M_\odot$. The inner structure of a molecular clump with a diameter of $0.1''$ can be traced by the high angular resolution of the ngVLA. Therefore, not only massive IMBHs ($M_{\rm BH} \sim 10^4$–10^5 $M_\odot$) but also lighter ones ($M_{\rm BH} \lesssim 10^3$ $M_\odot$) would possibly be found in the CMZ based on the observations toward HVCCs.

The ngVLA with long baselines may enable us to measure the proper motions of point sources even in the CMZ (at 8 kpc from the Sun). A transverse velocity of 100 km s^{-1} at a distance of 8 kpc corresponds to a proper motion of 2.7 mas yr^{-1},

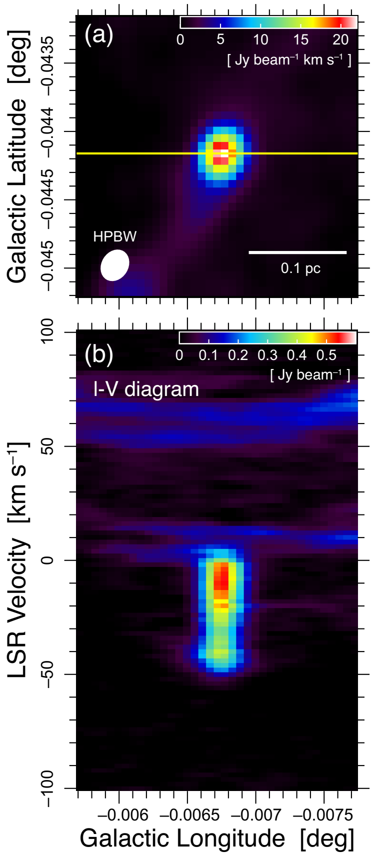

Fig. 2. (a) Integrated intensity map of the ultra-compact clump (UCC) toward HCN–0.009–0.044 in the HCN J=4–3 line obtained with the ALMA. The white ellipse in the lower left corner indicates the synthesized beam size ($0.87'' \times 0.71''$). (b) Longitude–velocity (*l*-*V*) diagram along the yellow line in the panel (a).

which is detectable with the ngVLA. If we can identify an IMBH candidate source associated with molecular gas streams constituting a HVCC, we will infer a line-of-sight velocity of the source by orbital fits to the gas streams. Thus, we may be able to constrain the three-dimensional velocities of IMBH candidates, which should be useful to understand their origins.

Hydrogen recombination lines may also be used in the search of IMBHs. Tsuboi et al. (2017) have suggested the possibility that IRS13E, which is an infrared source in the vicinity of Sgr A*, can contain a $\sim 10^4\ M_\odot$ IMBH based on the radio recombination line observations of the high-velocity ionized gas. We found the faint Pα line emission at 1.87 μm toward the dynamical center of HCN–0.009–0.044 (see Figures 2 and 3 in Takekawa et al. 2019a). This faint emission blob may be detectable by radio recombination lines with the high sensitivity of the ngVLA. The kinematic analysis of the ionized gas will provide valuable information to diagnose the presence of an IMBH.

As well as in the CMZ, broad-velocity-width features of molecular gas are possible probes of isolated BHs in the Galactic disk. Indeed, we have found several HVCC-like features in the disk, which are potentially driven by high-velocity plunges of isolated BHs (Yamada et al. 2017; Yokozuka et al. 2021). The total number of BHs in our Galaxy is predicted to be an order of 10^8 (e.g., Caputo et al. 2017). Some of them could be dynamically identified by the detailed spectral line observations. The ngVLA has much potential to find Galactic isolated BHs including IMBHs, contributing to understanding the origin of SMBHs and galactic evolution.

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