Astrometric observations of water maser sources toward the Galactic Center with VLBI

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Abstract. The Central Molecular Zone (CMZ) in the Galactic Center region shows outstanding non-circular motion unlike the Galactic disk. Although several models describing this non-circular motion are proposed, an uniform kinematic model of the CMZ orbit is not appeared. Three dimensional velocity information including proper motions will be critical to constrain the orbital models of the CMZ because most of models proposed are devised to reproduce the line-of-sight velocity profiles of the molecular clouds in this region. To reveal the dynamics of the Galactic center region, we conducted VLBI astrometric observations of 22 GHz water maser sources toward the Galactic center with VERA. By measuring parallaxes and proper motions, we can identify whether each source is actually located in the CMZ or not, and identify the three dimensional positions and velocities in the non-circular orbit if the source is located in the CMZ. We show the results of astrometric study for several maser sources associated with molecular clouds toward the Galactic center including Sgr B2 complex and Sgr D HII region. The parallax measurement toward Sgr B2 obtained the parallax of 0.133 ± 0.038 mas, and its proper motions indicated that Sgr B2 complex is moving toward the positive Galactic longitude with $V = 100\,\mathrm{km\,s^{-1}}$ relative to Sgr A*.

1. Introduction

The Central Molecular Zone (CMZ), which ranges from -2 to $+2$ degree of the Galactic longtude, has very peculiar properties. The molecular gas density is very high ($n = 10^3 - 10^5\,\mathrm{cm^{-3}}$), the line width of the molecular emission is larger ($\Delta V = 20 - 50\,\mathrm{km\,s^{-1}}$), and the star formation rate (SFR) is quite low despite such high density. Recently, this inefficient SFR is considered to be come from the dynamical feature of the CMZ. Then, two representative models are proposed to explain these properties in the CMZ. First model is closed orbit model proposed by [1]. In this mode, the orbital velocity is constant, and the star formation is triggered by cloud-cloud collision in the intersection between different orbits. Another model is open orbit model proposed by [2]. In open orbit model, the tidal compression in the orbit triggers the star formation. Understanding the dynamical model of the CMZ is important to study not only whole property of the CMZ but also star-formation of individual molecular cloud in the CMZ.

22 GHz water maser emission is known as an indicater of active star forming regions and regions of extremely dense gas. This is a useful tool to study the kinematics and environment around young, massive stars. In the Galactic center, 22 GHz water maser is the most appropriate

maser line because there are few sources which have sufficient flux densities that we can detect with VLBI in other maser lines such as 6.7 GHz methanol and 1.6 GHz OH masers.

The giant molecular cloud complex Sagittarius B2 (hereafter Sgr B2) is one of the most active star forming region in the Galaxy, which has a projected distance of about 100 pc from the Galactic center. This source consists of three major star formation sites, Sgr B2(N), Sgr B2(M), and Sgr B2(S) [3,4], which are aligned from north to south with separation of 45 arcsec with each other. A number of observations have been conducted to reveal the nature of this source in radio continuum [5-7], molecular lines [8-11], and recombination lines [12,13].

The parallax of Sgr B2(M) and B2(N) have already been measured with VLBA to be 0.130 ± 0.012 mas and 0.128 ± 0.015 mas, respectively [14]. They also measured the orbital velocity of Sgr B2 complex in the Central Molecular Zone (CMZ) using the measured proper motion and LSR velocity. However, the measured proper motion still contains a large uncertainty of $\sim 1\,\mathrm{mas\,yr^{-1}}$ because they did not take into account of the internal motions of H_2O maser spots. To determine more accurate position and orbital velocity of Sgr B2 in the CMZ, we should measure and correct the internal motions of maser spots.

Water maser source G0.21 is located near G0.253+0.016, which is a candidate of a progenitor of massive star cluster. Because the line-of-sight velocity of the water maser is close to that of molecular emission ($V_{\mathrm{lsr}} = 30$–$40\,\mathrm{km\,s^{-1}}$) [15]. This source is supposed to be located at the front side of the CMZ. In open orbit model, the location is just after passing the pericenter of the orbit, and molecular cloud suffers strong compression due to tidal force. Eventually, the formation of high mass star cluster is triggered.

In this proceeding, we show two astrometric results of water masers associated with Sgr B2 and G0.21 by using VLBI observations. Note that the results for G0.21 are preliminary, and it could be changed by future detail analysis.

2. Observations

We conducted VLBI observations of H_2O maser sources associated with Sgr B2 complex at a rest frequency of 22.235080 GHz using VERA during the period from 2014 to 2017. The number of observation epochs was two in 2014, two in 2015, nine in 2016, and two in 2017. In each epoch, the on-source time for Sgr B2 complex was about 1 hour. The reason for such short on-source time is that a series of observations is aimed to observe other target maser sources, and that Sgr B2 was observed as a phase referencing source. The target maser source Sgr B2 and the position reference source J1745−2820 were simultaneously observed using the dual-beam system of VERA. The separation angle between two sources is 0.33°.

We also conducted wide-band VLBI observation of H_2O masers associated with G0.21 from 2018 to 2020. We observed one epoch in 2018, three epochs in 2019, and one epoch in 2020.The position reference source J1745−2820 were observed with the wide-band mode of VERA, whose bandwidth is 2040 MHz, and it is eight times larger width than usual observing mode.

3. Results and duscussion

3.1. Sgr B2

From phase-reference observations, we measured the parallax and absolute proper motions relative to the extra-galactic source J1745-2820. A maser spot at $v_{\mathrm{LSR}} = 59.58\,\mathrm{km\,s^{-1}}$ was detected over ten epochs from 2014 to 2016. The positions of the maser spots in the phase-referenced map are affected by linear motions and the annual parallax. Then, we could derive the proper motions in right ascension $\mu_\alpha \cos\delta$ and in declination μ_δ, the initial positions in right ascension $\alpha_0 \cos\delta$ and in declination δ_0, and the parallax π for the maser spot, using least-squares fitting. Figure 1(a) shows the projected motion of the maser spot. The direction of absolute proper motion goes from northeast to southwest. This is almost parallel to the Galactic plane. In figure 1(b), the motion in the directions of RA and Dec are shown as a function of time.

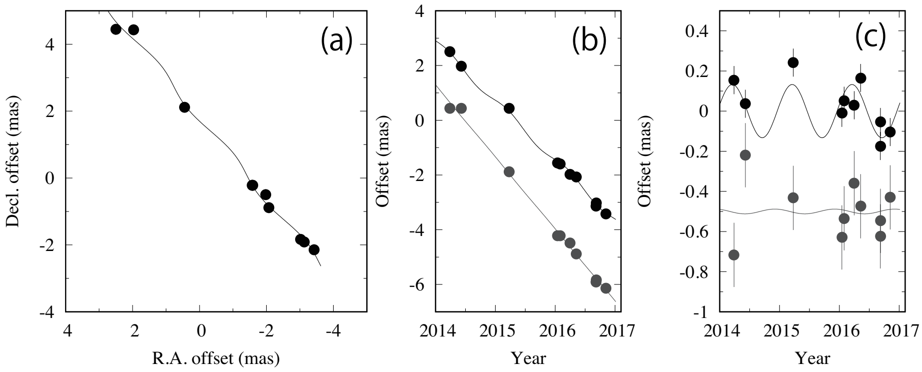

Figure 1. (a) Absolute proper motions of the maser spot at $v_{\rm LSR} = 59.58\,{\rm km\,s^{-1}}$ in Sgr B2(M) region. Filled circles show the observed points from phase referencing. (b) Motions towards R.A. and Dec. as a function of time. Black circles show the motion in the R.A. direction, and gray circles show the motion in the Dec. direction. (c) Result of parallax fitting. Error bars are evaluated so that a χ^2 value in the model fitting becomes unity.

By subtracting the expected linear motions from figure 1(b), we obtained the parallax shown in figure 1(c). The obtained parallax is 0.133 ± 0.038 mas, and proper motions in the Galactic coordinate is $(\mu_l, \mu_b) = (-4.17\pm0.19, -0.34\pm0.13)\,{\rm mas\,yr^{-1}}$. These parallax and proper motions are calcuated and fitted by using equations described in [16].

When we compare these velocities with the existing models, we found that Sgr B2 complex is located at the upstream of vertex of the orbit. This is consistent with the position of Sgr B2 complex suggested by the open orbit model in [2], in which the star-forming activity in the Sgr B2 complex is triggered by the tidal compression during their pericenter passage. Sgr B2 is located at the upstream of vertex of the orbit in the open orbit model, while in the closed orbit model, this is located at the vertex at which two different orbital families intersect. Also, the proper motions predicted in [2], $(\mu_l, \mu_b) = (-4.21, -0.95)\,{\rm mas\,yr^{-1}}$, is almost consistent with our results. It also supports the open orbit model in the CMZ.

3.2. G0.21

We succeeded to detect fringes from the phase reference source J1745−2820 thanks to the wide-band mode of VERA. Eventually, we could conduct astrometric observations for relatively weak water masers (2–3 Jy) associated with G0.21 region.

In figure 2, we show a preliminary results of astrometric observations for G0.21. For maser spots at $v_{\rm LSR} = 47.48\,{\rm km\,s^{-1}}$ and $v_{\rm LSR} = 47.06\,{\rm km\,s^{-1}}$, we measured their proper motions as $(\mu_l, \mu_b) = (-0.179, -0.975)\,{\rm mas\,yr^{-1}}$ and $(\mu_l, \mu_b) = (-0.568, -1.249)\,{\rm mas\,yr^{-1}}$, respectively. When we compare these value with the prediction from two representative models, $(\mu_l, \mu_b) = (-1.63, -0.56)\,{\rm mas\,yr^{-1}}$ for open orbit model, and $\mu_l = -3\,{\rm mas\,yr^{-1}}$ for closed orbit model, our result also prefers open orbit model to closed orbit model in G0.21 region.

4. Summary

The dynamics of the Central molecular zone is important to understand (i) the gas flow into the central region of the Galaxy, and (ii) the formation of stars in the Galactic center. Between two representative models, the open orbit model can reproduce the properties of star-formation in the CMZ especially fro G0.253 to Sgr B2. To increase the number of sources for reconstructing the orbital models in the CMZ, the developing of astrometry mode of EAVN, wide-band receiver, and accurate geodesy is important.

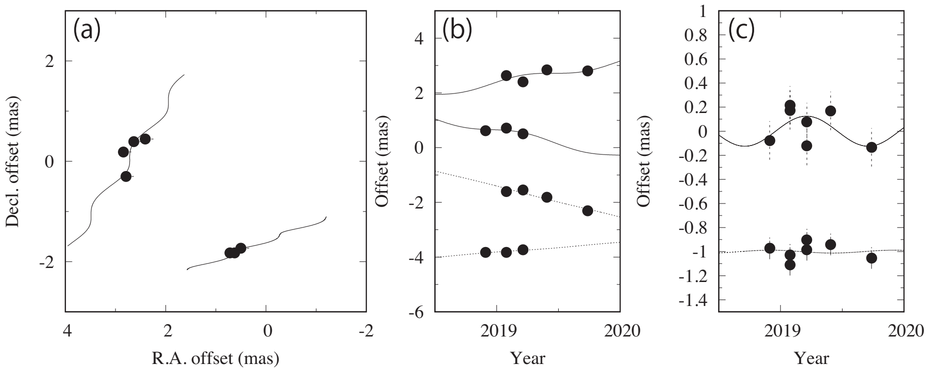

Figure 2. (a) Absolute proper motions of the maser spot at $v_{\rm LSR} = 47.48\,{\rm km\,s^{-1}}$ and $v_{\rm LSR} = 47.06\,{\rm km\,s^{-1}}$ in G0.21. Filled circles show the observed points from phase referencing. (b) Motions towards R.A. and Dec. as a function of time. Black circles show the motion in the R.A. direction, and gray circles show the motion in the Dec. direction. (c) Result of parallax fitting. Error bars are evaluated so that a χ^2 value in the model fitting becomes unity.

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