Infalling gas onto the Galactic center Circumnuclear Ring

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Abstract. The central region of our Galaxy (Sgr A*) is the nearest galactic center harboring a massive black hole. The environment around Sgr A* is a topic of interest to diverse fields. We are interested in gas feeding from giant molecular clouds (GMC) within 10 pc of the Galactic center to the Circumnuclear Ring/Disk (CND), which is presumable "lay-down bay" of infalling gas toward Sgr A*. In order to reveal the mechanism, we observed the CND and its surroundings in SiO and H\(^{13}\)CO\(^+\) lines using Nobeyama Millimeter Array (NMA). We depict the CND clearly in both lines and some molecular streamers to the CND in only SiO line including one new detection. The line intensity ratios at overlapping points of streamers with the CND are higher (I(SiO)/I(H\(^{13}\)CO\(^+\)) > 6) than the average of CND (2-4). This is a strong evidence indicating these streamers are connecting to the CND. Some components at the outer region of the CND are also detected in both lines. We also estimate the rotation velocity of the CND as 110±10 km s\(^{-1}\) and of just a bit outside from the CND as 93±14 km s\(^{-1}\). The estimation of the rotation velocity in the distance range of 5-10 pc from the Sgr A* has a great meaning since there have been few report about the kinematic parameters at just outside of the CND.

1. Introduction
The central region of our Galaxy is the nearest galactic center harboring a massive black hole [1,2]. This gives us the opportunity to observe the phenomena particular to the galactic center region of normal galaxies using existing telescopes. These for the external galaxies can be observed only with future huge telescopes. The environment around Sgr A* is a topic of interest to diverse fields.

The Circumnuclear Ring (CND) is a ring-like structure with a radius of 2 pc surrounding Sgr A*. The CND has been imaged in far-infrared continuum and radio molecular lines (e.g.[3]). This consists of neutral gas and dust. The ionized gas streamers appear to be revolving around Sgr A*, originating at the inner edge of the CND. But it is not clear whether they fall to Sgr A* itself, or not [4]. It has been proposed that the CND is a supply source of ionized material accreting to the massive central black hole, Sgr A* [5].

The CND should be destabilized by perturbation with Giant Molecular Clouds (GMCs). If feeding to the CND stops, the CND structure will disappear. If the CND is a persistent structure, the question remains as to how it is maintained. One possible mechanism is that the CND is supplied with material from the molecular clouds existing within 10 pc of the Galactic...
Center [3]. There are two GMCs within projected distance of 10 pc: 20 km s$^{-1}$ cloud and 50 km s$^{-1}$ cloud to the south and east of the CND, respectively.

Recently this region has been studied extensively by Ho and collaborators using VLA (NH$_3$ emission lines, [6-9]), and by Montero-Castano et al. [9] using SMA (HCN $J$=4-3, 2006). It is suggested that the molecular streamers from the GMCs feed the CND (e.g. [11]). Although these molecular streamers increase velocity widths and temperatures as approaching from GMC to the CND, there is no significant evidence of this assumption because of shortages in sensitivity and resolution.

If the hypothesis on the mechanism maintaining the structure of the CND mentioned above was true, there would be a shock at the overlapping points on the CND with candidate paths of infalling molecular gas. The detection of shock must be a good evidence of their interaction. On this purpose we carried out an observation toward the CND in the Galactic Center in SiO $J$=2-1 $v$=0 ($\nu$=86.847 GHz), and H$^{13}$CO$^+$ $J$=1-0 emission line ($\nu$=86.754 GHz), using Nobeyama Millimeter Array (NMA) at the Nobeyama Radio Observatory (NRO). SiO $J$=2-1 line is a well known shock tracer since it arises as the SiO abundance increases from Si atoms coming out from dust because of the heating by the shock. On the other hand, H$^{13}$CO$^+$ $J$=1-0 is believed to be a good tracer of mass distribution. Observations with molecular lines such as CS or CO have been conventionally used as a tool to obtain mass distributions in the Galactic Center region. But Handa et al.(2006) [12] presented a question on the reliability of the mass information obtained from these molecular line observations because of their optical depths. In that paper they suggest the possibility of H$^{13}$CO$^+$ $J$=1-0 emission line as a better indicator of mass distribution due to its thin optical depth even in the Galactic Center region.

2. Evidence of interaction between the streamers and the CND
We carried out the observation using the Nobeyama Millimetre Array (NMA), with the angular resolution of $9''\times 4.9''$ and the velocity resolution of 6.9 km s$^{-1}$. Since the field of view of NMA at 87 GHz(77''$') isn’t wide enough to cover the the whole structure of the CND, we observed 8 fields.

In addition to the detection of the CND in both SiO and H$^{13}$CO$^+$ emission lines, we detected the SiO emission from a structure which elongates from 20 km s$^{-1}$ cloud toward the CND, named the Southern Streamer [Okumura et al., 1989], at the positive $V_{LSR}$. We also detected another streamer-like structure (New Streamer) on the southwest of the CND with the SiO line at the negative $V_{LSR}$. H$^{13}$CO$^+$ $J$=1-0 emission line is also detected for the CND, but it is faint in the streamers which are significant in SiO emission line. The velocity-integrated maps of SiO and H$^{13}$CO$^+$ lines are shown in Fig.1. In both figures, the contour indicates the red-shifted component, dashed-line contour for the blue-shifted component. The star symbol and thick broken black line indicate the position of Sgr A* and the position of the CND, respectively.

2.1. Widening of the line width
The position-velocity maps, being cut along the lines indicated in Fig.1, are shown in Fig.2. These streamers seem to show an increase in velocity as they approach to the CND, and velocity broadening at the overlapping points with CND. From left side panel in fig.2, one can see that the southern streamer has line-of-sight velocity of 20 to 30 km s$^{-1}$, which clearly indicates that this molecular streamer has a relation with the 20 km s$^{-1}$ GMC at the south of it. Then there is a sudden widening in the velocity width as the streamer reaches to the edge of the CND, to over 100 km s$^{-1}$, having two peak velocities include one of 20 km s$^{-1}$. As the another peak velocity shows the same velocity with the one which is expected from the CND rotation, this velocity broadening may show the mixing of the velocity as the material approaches to the CND through the southern streamer.
Figure 1. The velocity-integrated maps of SiO (left) and \(^{13}\)CO\(^+\) (right) lines. contour: red-shifted component, dashed-line contour: blue-shifted component, thick black line: position of the CND, star mark: position of Sgr A\(^*\).

The clear velocity width broadening is seen also at the point on which the new streamer overlaps with the northwest of the CND (right panel of fig.2). The line-of-sight velocity of the new streamer changes as it approaches toward the CND in projection. It at least indicates that the new streamer would have velocity gradient in the direction to the CND.

2.2. Line ratio of SiO \(J=2-1\) over \(^{13}\)CO\(^+\) \(J=1-0\)
A ratio of SiO \(J=2-1\) over \(^{13}\)CO\(^+\) \(J=1-0\) line indicates the fractional abundance of SiO. The number of SiO molecule increases when a certain shock event occurs because the shock would heat the dust up till it extricates Si atom, which would then form SiO molecule.

The ratio at each position on the CND is shown in Fig.3. The position angle is taken from the west to the CND as 0\(^\circ\) and in counter-clockwise along the inner ellipse shown in the right panel of fig.3 which indicates the position of the CND detected in HCN emission line in the previous researches. High ratio of SiO \(J=2-1\) over \(^{13}\)CO\(^+\) \(J=1-0\) line, bigger than 6, is found at the place where the Streamers seem to be overlaid on the CND (around 50\(^\circ\) and 130\(^\circ\) in position angle). This means that the fractional abundance of SiO molecule surely increases at the points where the candidate molecular streamers seem to overlap with the CND in projection. Other areas of the CND show the average value in the Galactic Center region, 2-4 [12]. The streamers also have the average line ratio values along them but only at the overlapping points with the CND. This implies that there is a strong shock at the contacting area for the CND.

3. Rotation velocity of the Galactic Center region
3.1. Rotation velocity of the CND
With the observation of 8 pointings, the whole structure of the CND and the near surroundings are pictured in SiO and \(^{13}\)CO\(^+\) emission lines. Besides the CND structure which has been detected in other molecular lines, we also detect the emission of both lines observed at the just outer region of the CND, especially at the northeast to it. This structure has been detected
Figure 2. Position-velocity maps along the Southern Streamer (left) and the New Streamer (right). Positions are referred from the left panel of Fig. 1.

Figure 3. The graph on the right side shows ratio of SiO \( J=2-1 \) over \( \text{H}^{13}\text{CO}^+ \ J=1-0 \) line at each position along the inner dashed-line circle in the left panel, which indicates the position of the CND detected with HCN emission line. The position angle is taken from the west to the CND as 0° and in counter-clockwise along the inner ellipse shown in the left panel. The overlapping points on the CND with two molecular streamers have larger values compared with other region in the CND.
Figure 4. Rotation velocities along the inner and the outer region of the CND. The position angle is taken to refer the west of the CND as 0°. The circle marker indicates the velocities at the each position angle along the inner ellipse shown in the left panel of Fig.3, and the triangle is for outer ellipse. The fitting velocity curves for inner and outer ellipse are shown in solid and dashed lines, respectively.

in HCN J=1-0 emission line too, implying that it is not only shock enhanced but also is real feature as molecular clump. Assuming these molecular fractions are a part of the CND and move together with it, the rotation velocity curves can be plotted for both the inner and the outer region of the CND. Here we assume the inclination angle of the CND from the Galactic plane to be 45°, position angle of its major axis to be 25°. Fig.4 shows the velocity curves measured for the 2 regions along the ellipses which is indicated in the left panel of fig.3. The inner ellipse indicates the position of the CND which has been detected in HCN J=1-0 and other molecular lines. The outer ellipse is chosen to trace the newly detected outer ridge in the northeast to the CND, with the central focus on the Sgr A*. The circle marker shows the velocity at each position angle along the inner ellipse and the solid line is the fitted velocity curve for it. The triangle marker shows the velocity along the outer ellipse and the dashed-line is the fitting curve for it. From the rotation curves we estimate the rotation velocity of 110±10 km s⁻¹ for the inner ellipse.
3.2. Rotation velocity of just outer region of the CND

We find a shift in the peak position of the rotation velocity between inner and outer ellipse. The inner ellipse has the peak velocity at the position angle of about 70° counter-clockwise from the east, while the outer ellipse has the peak velocity at about 100°. The shift in position angle is about 20° to 30°. One interpretation for this shift might be of an inward motion at the outer ellipse toward the center. However, to explain this apparent shift in position angle, the radial velocity of 40 to 50 km s\(^{-1}\) would be required. This would seem rather too extreme situation to consider that the materials in the CND rotates with the velocity of about 100 km s\(^{-1}\) and also infalls with such a high velocity at the same time. The alternate explanation would be given by considering the shift in the position angle of the major axes. Assuming the major axis of the outer ellipse to be in the direction of the peak velocity it has, the rotation velocity of 93±14 km s\(^{-1}\) is estimated.

3.3. Rotation curve for the Galactic Center region

Fig. 5 shows the rotation velocity for each distance from Sgr A\(^*\) in scale of pc from 0.01 to 100. Black marker from 0.07 to 1.5 pc from the Galactic Center shows the rotation velocity estimated from the stellar motion (e.g. [13]). Genzel and his collaborators estimated the rotation velocities at the distances shown in open-circle marker [5]. The rotation velocities at over 10 pc was estimated from the kinematics of molecular clouds, shown in filled-circle marker [14]. Apparent from this graph, the rotation velocity at the distance range from 1 to 10 pc from Sgr A\(^*\) has
not been intensely studied compared with the inner/outer region from this distance range. Our results put the points (with error bars) at exactly within this distance range. Assumed the Keplerian motion with a central mass of $3.6 \times 10^6 M_\odot$, the calculated rotation curve is shown with solid line in this figure. The rotation velocities for the CND and the just outer region of the CND seem to be on the line, indicating the molecular gas and dust of the CND would follow the Keplerian motion. Although we report the velocity at only from two radius from Sgr A*, it should be noted to be able to estimate the rotation velocity in just a little bit outer region from the CND.

4. Conclusion

We observed the central 2-5 pc region of our Galaxy with SiO $J=2-1$ and $H^{13}$CO$^+$ $J=1-0$ lines, using Nobeyama Millimeter Array. Some molecular streamers are detected in SiO line, which are very faint in $H^{13}$CO$^+$ line. The velocity widths are clearly broaden where the streamers seem to hit the CND. The line intensity ratio of SiO over $H^{13}$CO$^+$ line ($I$(SiO)/$I$(H$^{13}$CO$^+$)) significantly increases at the overlapped points of the CND and these streamers ($>6$) compared to the average ratio in other region of the CND(2-4). We strongly suggest that these streamers physically interact with the CND. We also estimate the rotation velocity of the CND (110±10 km s$^{-1}$) and of an orbit just a bit outside from the CND (93±14 km s$^{-1}$).

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