Interaction between the SNR Sagittarius A East and the 50-km $s^{-1}$ Molecular Cloud

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Abstract. We performed high-resolution observations of the Galactic Center 50-km $s^{-1}$ molecular cloud in the CS $J = 1 - 0$ line using the Nobeyama Millimeter Array. The 50-km $s^{-1}$ molecular cloud corresponds to a break in the Sagittarius (Sgr) A east shell. A very broad and negative velocity wing feature is detected at an apparent contact spot between the molecular cloud and the Sgr A east shell. The velocity width of the wing feature is over 50-km $s^{-1}$. The width is three times wider than those of typical Galactic Center clouds. This strongly suggests that the shell is interacting physically with the molecular cloud. The asymmetric velocity profile of the wing feature indicates that the Sgr A east shell expands and crashes into the far side of the molecular cloud. About 50 clumps are identified in the cloud using CLUMPFIND. The velocity width-size relation and the mass spectrum of clumps in the cloud are similar to those in Central Molecular Zone (CMZ).

1. Introduction

The Galactic Center region is the nearest nucleus of a spiral galaxy. We can observe unique features there related to star formation fed by infalling molecular clouds in detail using present radio telescopes. Such features include young and highly luminous star clusters in the Galactic Center region: the Arches cluster, Quintuplet cluster, and central cluster [1]. It is an open question what mechanism is responsible for the formation of such bright star clusters around the Galactic Center. Molecular clouds in the Galactic Center region are much denser, warmer, and more turbulent than disk clouds, and they have filamentary shapes with several clumps [2] [3] [4]. Detailed observations of the dense molecular clouds of the Galactic Center region should provide unprecedented information about the mechanism of star formation in the Galactic Center region. The “50-km $s^{-1}$ molecular cloud,” which is located only 3′ from Sagittarius (Sgr) A* is a most remarkable Galactic Center molecular cloud (see figure 3 and 4 in [4]), being associated with compact HII regions [5][6]. Moreover, the morphological relationship between the 50-km $s^{-1}$ molecular cloud and the Sgr A east shell, which is presumably a luminous and young SNR located in the Galactic Center region, suggests a physical interaction [7]. The interaction of SNR with the molecular clouds may play an important role in star formation in the Galactic Center region, exactly as in the Galactic Disk region. In addition, the statistical properties of the molecular clouds, for example the mass spectrum of the molecular clumps, could reveal how the clouds are changed before and after interaction with a SNR. We have observed the detailed structure of the 50-km $s^{-1}$ molecular cloud in the CS $J = 1 - 0$ line using the Nobeyama Millimeter Array (NMA). CS emission is expected to be nearly free from the strong contamination near 0 km $s^{-1}$.
from the foreground and background disk molecular clouds because it has a high critical density, \( n(H_2) \approx 10^4 \text{ cm}^{-3} \). Only the NMA can make high resolution observations in the CS \( J = 1 - 0 \) line. Throughout this paper, we will adopt 8.5 kpc as the distance of the Galactic Center. At this distance, 1 pc corresponds to about 24".

![Figure 1](image)

**Figure 1.** Relative location among the FOV of NMA (thick circle), the 50 km s\(^{-1}\) molecular cloud in CS \( J = 1 - 0 \) line from the 45-m telescope (contours), and Sgr A east at 5 GHz.

### 2. Observations and Data Analysis

The 50-km s\(^{-1}\) molecular cloud, which is centered at \( l = 359^\circ 58'54.8'' \), \( b = -0^\circ 4'18.8'' \), was observed with NMA in the CS \( J = 1 - 0 \) line (48.990964GHz). The field of view (FOV) was about 140" at 49 GHz, which was the FWHM (Full Width at Half Maximum) of the 10-m antenna elements of the NMA. Figure 1 demonstrates the relative location of the FOV, the 50 km s\(^{-1}\) molecular cloud in CS \( J = 1 - 0 \) line from the 45-m telescope [4], and the Sgr A east shell at 5 GHz [8]. The FOV included the 50-km s\(^{-1}\) molecular cloud and the east edge of Sgr A east shell. It was difficult to make a mapping of the field in the vicinity of a strong source such as Sgr A west because the side lobes of a strong source induce artifacts that overwhelm faint structures. We chose the field center so that Sgr A west was settled in the first null of the element antenna response of the NMA. Thus the resultant maps were almost free from the side-lobe effect of Sgr A west. The receivers of the NMA at 49 GHz were SIS mixer receivers. The system noise temperature, including atmospheric noise, was about 400 K during the observations. The back end was a FX-type digital correlator. The total velocity coverage and velocity resolution were 490 km s\(^{-1}\) and 0.48 km s\(^{-1}\), respectively. We used NRAO530 as the phase and the gain calibration source, for which the flux density during our observations was 7.0 Jy at 49 GHz. The absolute flux density scale was established using Uranus and Mars.

In order to make maps, we used the CLEAN method in NRAO AIPS package. The size of the synthesized beam is \( 8.5'' \times 10''(\phi = 24^\circ) \) with a natural weighting, which corresponds to about 0.35 pc \( \times 0.42 \) pc. Features with spatial extents larger than 1' are resolved out. Therefore, the NMA is best used as a spatial filter to find compact components. It should be noted here that all maps in this paper are not corrected for the primary beam attenuation of the element antenna. Finally, a comparison of the C\(^{32}\)S \( J = 1 - 0 \) and C\(^{34}\)S \( J = 1 - 0 \) lines observed by the NRO 45-m telescope indicates that average optical depth of the C\(^{32}\)S \( J = 1 - 0 \) line is about 3 in the central part of the 50-km s\(^{-1}\) molecular cloud [4]. We keep in mind in the following analysis that the CS \( J = 1 - 0 \) line is moderately optically thick.
3. Results

Figure 2 shows the velocity channel map taken with the NMA of the CS $J = 1 - 0$ emission toward the 50 km s$^{-1}$ molecular cloud. The integrated velocity width of each panel is 3.8 km s$^{-1}$. The r.m.s. noise levels of the resultant maps are about 0.05 Jy beam$^{-1}$ at the centers of the fields. The molecular cloud can be detected in panels with $V_{LSR} = 10.6 - 83.2$ km s$^{-1}$. The molecular cloud is resolved into many clumps and/or several filaments in the channel maps. The Sgr A east shell is located northwest of the cloud, but it is already faded out at these frequencies. In the velocity range of $V_{LSR} = 10.6 - 52.7$ km s$^{-1}$, the molecular cloud is elongated mainly from the lower left to the upper right. The clouds with more positive velocities have more complicated structures. We used CLUMPFIND on FITS data of this channel map in order to find molecular clumps automatically. These will be discussed in the next section.

Figure 3 shows a velocity-integrated map of the 50-km s$^{-1}$ molecular cloud. The velocity range is $V_{LSR} = 8 - 72$ km s$^{-1}$, and covers almost all of the 50-km s$^{-1}$ molecular cloud. Although the molecular cloud in the lower-resolution map is smooth and has a triangular shape (also see figure 1), the higher-resolution map shows that the CS $J = 1 - 0$ intensity in the cloud is concentrated in three components. The emission detected within the FOV by the NMA is about 40% of that detected by the NRO 45-m telescope. The circle superimposed on the figure shows the FOV of the NMA. The shaded contours in the figure indicates the continuum emission at 5 GHz of Sgr A east shell. The figure also shows the detailed morphological complementarity between the molecular cloud and Sgr A east shell. The western boundary of the molecular cloud apparently intrudes into the break of the Sgr A east shell, which is darker than other parts of the shell. A component is located at an apparent contact point of the 50-km s$^{-1}$ molecular cloud with the Sgr A east shell, $l = -1.0', b = -4.2'$. This component is elongated along the boundary of Sgr A east shell. This component is identified in the channel maps with $V_{LSR} = 22.1 - 56.76$ km s$^{-1}$ (see figure 2). Another component is located in the break of the shell, $l = -1.3', b = -3.5'$. This is also elongated along the boundary. This component has velocity of $V_{LSR} = 25.9 - 71.8$ km s$^{-1}$ (see figure 2). The lower left component is located at one of the compact HII regions embedded in this cloud [5] [6]. The component has velocity of $V_{LSR} = 14.4 - 41.1$ km s$^{-1}$.

Figure 4 is the position-velocity diagram along the path through these components. The 50 km s$^{-1}$ molecular cloud is seen as an inclined ridge in the diagram. The velocity width increases up to 50 km s$^{-1}$ at the boundary. This velocity width is three times larger than those of other parts of the 50 km s$^{-1}$ molecular cloud and 10 times wider than those expected from their sizes based on the size-velocity width relation for disk clouds. This wide velocity dispersion presumably is produced by an interaction with the Sgr A east shell. Thus the boundary is a real contact point between the 50 km s$^{-1}$ molecular cloud and Sgr A east shell. In addition, the line profile at the contact point has only a negative velocity wing. H$_2$ emission [9] and collisionally-excited OH masers (1720 MHz) [10] have been observed around the boundary.

4. Discussion

As mentioned in the previous section, the line profile at the contact point has only a negative velocity wing. Although the poor sensitivity of the NMA may prevent us from detecting the positive velocity wing, any positive velocity wing is much weaker than the negative one. This suggests that the 50 km s$^{-1}$ molecular cloud is located in front of Sgr A east shell, so that the expanding shell crashes into the far side of the molecular cloud and blocks or suppresses the growth of shocked gas with positive velocity. As we know, the radio shadow or silhouette of Sgr A west against Sgr A east shell at low frequency indicates that Sgr A west is located in front of Sgr A east shell [11]. These facts suggest the positional relation among Sgr A west, Sgr A east, and the 50 km s$^{-1}$ cloud along the line of sight that is shown in figure 5. However, the distance between Sgr A west and east is not determined from these observations.

We used CLUMPFIND to find clumps in the 50 km s$^{-1}$ molecular cloud and to derive the
Figure 2. Velocity channel map from the NMA of CS $J = 1 - 0$ emission toward the 50-km s$^{-1}$ molecular cloud. The velocity width of each panel is 3.8 km s$^{-1}$. The numbers in the top left corners show the central LSR velocities of each panel. The size of the synthesized beam is 8.5" × 10" ($\phi = 24^\circ$).

Figure 3. Velocity-integrated map (contours) of the 50 km s$^{-1}$ molecular cloud overlaid on an image of Sgr A east at 5 GHz. The velocity range is $V_{LSR} = 8 - 72$ km s$^{-1}$.

Figure 4. Position-velocity diagram along the thick line in figure 3. The velocity width at the boundary between the 50 km s$^{-1}$ molecular cloud and Sgr A east (angular offset = 0') is three times wider than that of other parts of the cloud.

statistical properties of the clumps. About 50 clumps are identified in the cloud. As mentioned in the previous section, the 50 km s$^{-1}$ molecular cloud is located at the east boundary of Sgr A.
east shell. The ragged limb appears to fit in the break of Sgr A east shell. The components in the cloud are elongated along the boundary. Because the age of the Sgr A east shell is expected to be about 1500 years from X-ray observations [12], the interaction should have started several hundred years ago. However, even molecular gas with a velocity of 100 km s\(^{-1}\) moves only 0.1 pc in 1000 years. The time since the beginning of the interaction is too short to make the elongated component by a snowplow effect. Then the appearance may be caused by an increase of the fractional abundance of the CS molecule within the shock. It is unclear whether the statistical properties of the clouds will be changed in such a case.

Figure 6 indicates the velocity width-size relation of clumps in several regions. The velocity width-size relation is generally represented by \(\Delta V \simeq aR^{0.5}\) [13]. The relations of the Galactic Center molecular clouds [3][14][15] and Ori A GMC [16] are \(\Delta V \simeq 11R^{0.5}\) and \(\Delta V \simeq 2R^{0.5}\), respectively. The identified clumps are located on the smaller-size extension of the relation for Galactic Center molecular clouds. Although the clumps in the 50 km s\(^{-1}\) molecular cloud would be influenced by the incident shock wave, the velocity width-size relation in Central Molecular Zone (CMZ) is consistent with this cloud. Figure 7 shows the mass spectrum of clumps in the 50 km s\(^{-1}\) molecular cloud. The sampling mass of this observation is \(10^{2.5} - 10^{4.5} M_\odot\). The power law index in the cloud is \(\gamma \simeq -2\) \((dN/dM \propto M^\gamma)\). The figure also shows mass spectra in other regions of the CMZ for comparison. The sampling mass of the left and the right parts are \(10 - 10^2 M_\odot\) and \(10^4 - 10^6 M_\odot\), respectively. For wide mass range of \(10 - 10^6 M_\odot\), the index of the spectra is \(\gamma \simeq -2\). The power law index of the interacting region is also \(\gamma \simeq -2\), which is the same as that of the non-interacting region. There is no significant difference among these mass spectra. The power law index is also similar to that of disk clouds (e.g. Ori A GMC;[16]), even though the magnetic field is very strong (mGauss) and the velocity width is very wide (several 10 km s\(^{-1}\)) in the CMZ. It is not clear what causes these relations. However, they should provide information to help the discussion of star formation in the CMZ.

5. Conclusions
We have obtained 8.5” × 10” resolution maps in CS \(J = 1 - 0\) emission line of the 50-km s\(^{-1}\) molecular cloud in the Galactic Center region with NMA. The molecular cloud is physically interacting with Sgr A east. The velocity width-size relation and the mass spectrum of clumps identified in the cloud are similar to those in CMZ.
Figure 6. Velocity width-size relation of clumps in the 50 km s\(^{-1}\) molecular cloud, CMZ, and Ori A GMC.

Figure 7. Mass spectra of clumps in the 50 km s\(^{-1}\) molecular cloud (center), small molecular clouds in CMZ (left), and CMZ (right).

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