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Search for the CO-dark Mass in the Central Molecular Zone by using the ASTE 10-m Telescope

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Abstract. Atomic carbon (C^0) is one of the most abundant carbon-bearing species in the interstellar molecular gas, and its submillimeter lines are good tracers of low-density molecular clouds which are often dark in CO rotational lines. We present a new map of the central 150 pc region of the Milky Way in the 500 GHz [CI] line, which has been recently obtained with the ASTE 10-m telescope. The [CI] emission is brightest toward the central 5-pc region, where massive GMCs are absent. This [CI]-bright region is approximately centered toward Sgr A*, covering the entire circum-nuclear ring (CND) and the western part of the 50-km/s cloud. The C^0/CO abundance ratio is 0.5–2 there, and the highest ratio is observed toward the CND but just outside of the 2-pc ring of dense gas. This discovery may suggest that the CO-dark component occupies a significant fraction of the molecular gas in the circumnuclear region.

Keywords. Molecular clouds

1. Introduction

Fundamental structure and kinematics of the interstellar molecular gas are investigated traditionally by observing CO rotational lines, but the *Fermi* and *Planck* survey results unveiled that a few 10% of the interstellar molecular gas in the Milky way lacks detectable CO emissions. In the innermost part of galaxies, this CO-dark gas might be more common, or even the major form of the interstellar molecular gas. Ground-based and satellite observations of the submillimeter [CI] line showed that AGN and starburst galactic nuclei often have very high atomic carbon (C^0) to CO abundance ratios over unity, indicating that the common assumption that the elemental carbon is mostly confined in CO is not true in those harsh environments.

Although the central region of the Milky way Galaxy is classified as a quiescent nucleus, it has several features in common with those active galactic nucleus, such as past activities of Sgr A* and localized starbursts in Sgr A and B regions, which can reduce CO through dissociation by UV/X-ray/cosmic-ray radiations and shocks. The bar potential might also lower the CO abundance since the chemistry can be non-equilibrium in regions where the gas transported by the bar is accumulating. Observations of alternative tracers such as [CI] and [CII] lines are more important to known the 'true' molecular gas distribution in the CMZ, than in the Galactic disk region.

Among the alternative molecular gas mass tracer lines, the 500 GHz [CI] $^3P_1$–$^3P_0$ line is relatively easy to observe with ground-based large telescopes. In addition to the abundance of C^0, the low critical density ($n_{\rm crit} = 10^3$ cm^{-3}) and upper-state energy ($E_{\rm u}/k_{\rm B} = 24$ K) make the line a good tracer of CO-dark clouds for the Milky way's central molecular zone (CMZ). We present the current results of the [CI] observation

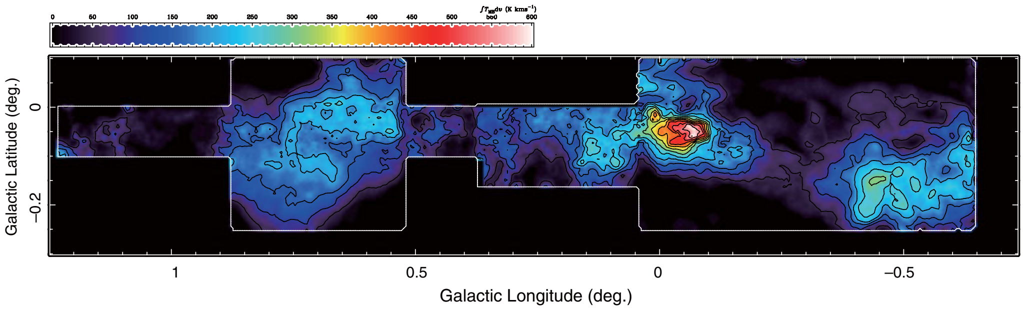

Figure 1. [CI] $3P_1$–$3P_0$ integrated intensity map. Contours are drawn at every 50 Kkm s^{-1}.

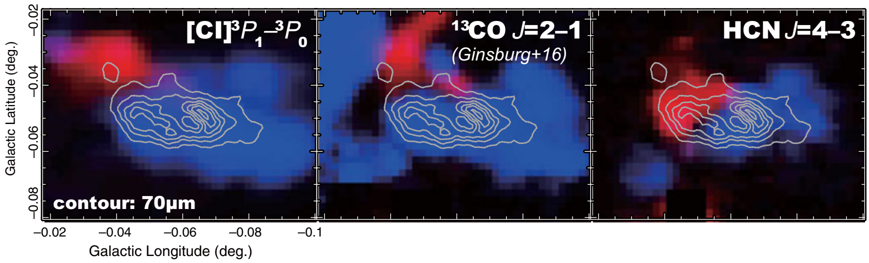

Figure 2. Circumnuclear disk in [CI] $3P_1$–$3P_0$, ^{13}CO J=2–1 (Ginsburg *et al.* 2016), and HCN J=4–3. The intensities are integrated over velocity ranges from 90 to 130 km s^{-1}, and from −110 to −40 km s^{-1}, respectively. Contours are for 70 μm continuum taken from the *Herschel* archival data.

that we have been conducting with the ASTE 10-m telescope and report discovery of regions with anomalously high C^0 abundance.

2. [CI]-Bright Clouds in the Sagittarius A Complex

Observations were conducted with the ALMA-type band-8 qualification model (QM) receiver installed on the ASTE 10-m telescope in Chile. The observations were made with the On-The-Fly (OTF) mode. The first season's observations mapped a near Galactic plane area from $l = -0^\circ.2$ to $+1^\circ.2$ (Tanaka *et al.* 2011), and the mapping region was extended to cover the three major GMC complexes, Sgr A, B, and C in 2015. Figure 1 shows the [CI] integrated intensity map smoothed with a 34″ Gaussian kernel. Overall structure of the [CI] line is consistent from the previously known dense gas maps. The [CI] emission is not strictly limited to the photo-dissociation regions (PDRs) on the cloud surface but is extended over the entire part of the GMCs, as seen for many nearby Galactic disk molecular clouds (e.g.Shimajiri *et al.* 2013). We did not find the trend that the [CI] is brighter in clouds with strong UV sources than in those not.

The most remarkable feature is very bright [CI] emissions from the Sgr A complex. The [CI] intensity peak in Figure 1 is approximately toward the Galactic center, where the [CI] to ^{13}CO J=2–1 intensity ratio is ~ 2, whereas the ratio is mostly ~ 0.5 outside the region. The [CI]-bright region covers the circum-nuclear disk (CND) and the 50-km s^{-1} cloud. Another massive GMC in the complex, the 20-km s^{-1} cloud, is not included in the [CI]-bright region despite its proximity to the nucleus on the projected sky plane.

The [CI] emission in the Sgr A complex is also remarkably different from the dense gas in the morphology. Figure 2 shows a close-up view to the Sgr A* in the [CI] and the HCN J=4–3 integrated intensities for the $v_{\rm LSR}$ ranges of the CND (90 to 130 km s^{-1} and −110

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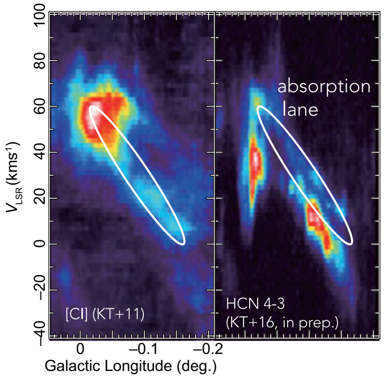

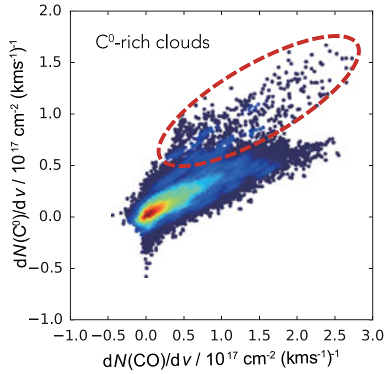

Figure 3. (left) Galactic longitude–velocity diagram for the Sgr A complex in [CI] and HCN J=4–3. The encircled region is observed in emission in the [CI] map, and in absorption in the HCN map.

Figure 4. (right) Scatter plot of C^0 column density versus CO column density.

to -40 km s^{-1} for the red- and blue-shifted portions). The [CI] distribution does not have the morphology of the well-known 2-pc radius ring seen in HCN and high-J CO lines. It is more spatially extended and elongated in the NE–SW direction, while its overall velocity gradient is consistent with the rotating motion of the CND. The [CI] intensity peak is at the SW end of the extension, which is just outside the 2-pc ring. Similar extended feature is seen in maps of low-J transitions of ^{13}CO, and also in millimeter HCN and CS lines (Takekawa *et al.* 2016 *in prep.*).

These results suggest that a large amount of low density gas is present in the central few parsec region of the CMZ, which has spatial distribution different from the dense gas structure, and has very high C^0 abundance. The presence of low density gas associated with the CND is also indicated by the low ^{13}CO J=2–1/1–0 intensity ratio for the [CI]-bright clouds, which is inconsistent with high temperature ($\gtrsim$ 200 K) and density ($\gtrsim 10^{4.5}$ cm^{-3}) measured from high-J CO data (Requena-Torres *et al.* 2012). We also found that the [CI] spectral peaks often coincide with HCN J=4–3 absorption dips in the Sgr A complex (Figure 3), which further supports that the [CI] emission primarily originates from low-density gas.

3. [C^0]/[CO] Abundance Ratio

We calculate the [C^0]/[CO] abundance ratios from our [CI] $^3P_1$–$^3P_0$ data. The gas kinetic temperature ($T_{\rm kin}$) and the molecular hydrogen volume density ($n_{\rm H_2}$) are assumed to be 100 K and 10^3 cm^{-3}, respectively, which are estimated from the ^{13}CO J=2–1/1–0 intensity ratio. We assume uniform temperature and density across the CMZ, since the measured intensity ratio shows small spatial variation.

Figure 4 plots the C^0 column density versus CO column density. In addition to the bulk component with relatively uniform abundance ratio of 0.3–0.5, a group of outliers with enhanced C^0 abundance is present. They mostly come from the 50-km s^{-1} cloud and the CND, whose average [C^0]/[CO] abundance ratios are 0.8 and 2, respectively. Considering that the typical [C^0]/[CO] ratio in the Galactic disk is 0.1–0.2 (Fixsen, Bennet, & Mather 1999), the amount of the CO-dark molecular mass contained in the [CI]-bright regions is equal to, or even higher than the gas mass visible in CO.

The mean abundance ratio for the CMZ is a factor of 2–3 higher than the Milky way average, but is still within the range of the value for nearby quiescent galactic centers,

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0.3–1 (e.g. Israel & Baas 2002; Rosenberg et a. 2015). Meanwhile, the ratio for the CND is closer to the values measured for AGN and starburst nuclei, where the $[C^0]/[CO]$ ratio exceeds unity. The molecular clouds in the innermost few parsec of our Galaxy might be in a similar environment to those active galaxies in terms of carbon chemistry.

The mechanism to increase C^0 in near the Galactic center is yet to be understood. High C^0 abundance in galactic centers is often attributed to high cosmic-ray flux there, and indeed the [CI]-bright regions found in the Sgr A complex is likely to be subjected to strong cosmic-ray field, since they are neighboring to the Sgr A* nucleus and the Sgr A-east supernova remnant. However, comparison with abundance variation of other chemical species shows that the high C^0 abundance is not accompanied by increase in other molecules that are expected to be enriched in the cosmic-ray dissociation region, such as HCO^+ (Harada *et al.* 2015). The C^0 abundance is found to be anti-correlated with the N_2H^+ abundance, which is favored by the model of shock chemistry or non-stationary PDR chemistry, although neither of them does not perfectly explain the difference in the chemical compositions in the C^0-rich cloud and in normal clouds. Detailed comparison with chemical model where all these effects are considered would be required to conclude the origin of the C^0-rich state in the Galactic center.

4. Conclusions and Future Prospects

We have found that the innermost part of the CMZ contains non-negligible amount of low-density, C^0-rich molecular gas. Hence the [CI] could be a powerful probe of molecular gas near the Galactic nucleus, which is possibly consumed to feed the nuclear activity or to form stars. We will investigate detailed structure of the [CI]-bright clouds near Sgr A* with our ALMA cycle-3 observations, with which the [CI] emission in the CND including the NE–SW extended part was mapped.

The CMZ [CI] survey is also being continued with the ASTE 10-m telescope. The new observing run will provide [CI] images of fainter [CI] sources, especially those in the 180-pc ring, with an improved sensitivity. Our previous observations detected several candidates of C^0-rich clouds in the 180-pc ring. They are possibly associated with the gas transportation and accumulation driven by the bar potential, which are hypothesized to be the trigger of the localized starburst activities in Sgr B2.

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