An extremely large column density cloud G0.11-0.11 in the Galactic Center Region

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Abstract. We obtained the detail map in H₁³CO⁺ and in thermal SiO lines of G0.11−0.11, which is a molecular cloud located between the Galactic Center Arc and Sgr A. From line intensity ratios we found H₁³CO⁺ line is optically thin, whereas the thermal SiO lines are optically thick for this cloud. The cloud has a large column density up to \(N(H₂) = (6 - 7) \times 10^{23} \text{cm}^{-2}\), which corresponds to about 640 – 740 mag in \(A_V\) or 10 – 12 mag in \(A_{25 \mu m}\). This is the largest known even in the Galactic Center region. The intensity ratio of SiO to CS lines suggests that emitting gas is highly inhomogeneous for SiO abundance on a scale smaller than the beam with about 35′.

1. Introduction

Large scale molecular line surveys have revealed that molecular clouds in the central \(\sim 100 \text{pc}\) of the Galaxy are different from those in the Galactic disk. For example, the incidence of relatively dense clouds is higher in the Galactic Center region. The Nobeyama Radio Observatory (NRO) CS survey has shown that density of most molecular clouds there is over \(10^4 \text{ cm}^{-3}\) [1].

Of dense molecular clouds in the Galactic Center region, the molecular cloud G0.11−0.11 is unique and one of the most interesting objects. It is located between Sgr A and the Galactic Center Arc (GCA). The CS observations reveal that G0.11−0.11 has a large molecular mass and large velocity width at the eastern¹ and western edges of the cloud. The eastern edge appears to have an interaction with the GCA [2]. G0.11−0.11 is bright at the X-ray fluorescent iron line [3], which suggests that dense gas in the cloud is excited by intense X-ray or high energy particles.

The previous molecular line observations of G0.11−0.11 were done in optically thick lines, such as CS and CO. The morphologies of G0.11−0.11 in CS and CO lines are similar. To obtain the physical properties of the cloud, we made observations in H₁³CO⁺ \((J = 1 - 0)\) line, which should be optically thin because of its very low abundance. At the same time, we present a high resolution view in thermal SiO lines. The thermal SiO lines are thought to be a good tracer

¹ In this paper, all directions on the sky are in terms of the galactic coordinates.
of hot and shocked regions, because this molecule is in gas phase only under high temperature environment [4].

2. Observations
We have observed G0.11−0.11 using the Nobeyama 45-m telescope, simultaneously observing at the spectral lines of H$^{13}$CO$^+$ $J = 1 − 0$ (86.75 GHz), SiO $J = 1 − 0$, $v = 0$ (43.42 GHz), and SiO $J = 2 − 1$, $v = 0$ (86.85 GHz). The full width at half maximum (FWHM) beam sizes at 43 and 86 GHz are 35′′ and 18′′, respectively. The observed region is a rectangular area of $0^\circ.4 \leq l \leq 0^\circ.10$, and $−0^\circ.10 \leq b \leq −0^\circ.04$, which covers the whole cloud. The spacing of the observation grid is 20′′, which corresponds to 0.82 pc at the distance to the Galactic Center, 8.5 kpc. The main beam efficiencies at 43 and 86 GHz are 0.81 and 0.50, respectively. The velocity resolutions at 43 and 86 GHz are 0.87 km s$^{-1}$ and 0.44 km s$^{-1}$, respectively, although we smoothed all spectra to be with 5 km s$^{-1}$ resolution.

3. Results
3.1. Features and morphology of the cloud
Figure 1 shows the integrated intensity maps in the three lines in the velocity range of $15 \leq V_{\text{LSR}} \leq 45$ km s$^{-1}$. The spatial resolutions are adjusted to 45′′ by applying gaussian convolution. The appearance in the SiO lines resembles that in the CS $J = 1 − 0$ line (see Fig. 1 of [2]).

However, several differences are apparent in the images in the H$^{13}$CO$^+$ $J = 1 − 0$ and SiO lines. The H$^{13}$CO$^+$ $J = 1 − 0$ intensity is significantly concentrated to the southern half of the cloud, although the cloud seems to extend beyond $b \geq −0^\circ.06'$ in SiO and CS images. These discrepancies are presumably due to the difference in optical depths between the SiO and H$^{13}$CO$^+$ lines (see detail in Section 4.1). Namely, the H$^{13}$CO$^+$ $J = 1 − 0$ line intensity traces the column density, but the SiO lines do not. Thus, G0.11−0.11 shows significant difference in column density below and above a front at $b = −0^\circ.06'$. G0.11−0.11 shows four distinctive features in these lines. Along the eastern edge of the cloud, a prominent ridge is seen in all the three lines. We dub it E-ridge hereafter (as indicated with a solid line in Figure 1). At $l = 0^\circ.07'$, it extends from $b = −0^\circ.06'$ to $b = −0^\circ.09'$ perpendicular to the Galactic plane. On the northern end of the E-ridge, a peak is seen in both the SiO lines at...
l = 0°8', b = −0°5′20″ (peak A, hereafter). At l = 0°6′20″, b = −0°5′20″, another peak (peak B) is seen in the SiO lines. The other prominent feature is a peak at l = 0°6′, b = −0°8′ (peak C). Figure 1 illustrates these features.

The E-ridge extends for 3′ in the Galactic latitude, equivalent to 7 pc at a distance of 8.5 kpc. A corresponding feature is also seen in the CS line (Fig. 2 in [2]). The E-ridge is extended in the direction parallel to the GCA. This morphology may suggest an interaction of the molecular gas with the GCA. However, this interaction is probably not so strong, if it exists, because the E-ridge is not the most prominent feature in the SiO image. In the H$^{13}$CO$^{+}$ $J = 1 − 0$ map the E-ridge is also distinguishable, but less prominent than in the SiO lines, and very weak in $b > − 0°6′$.

The peak A is seen in the SiO maps between 10 km s$^{-1} < v_{LSR} < 35$ km s$^{-1}$. At the high-red-shift end, the peak A is merged with the ridge along the Galactic plane through the peak B. In the SiO line images, the peak A appears to be somehow connected with the E-ridge. However, the H$^{13}$CO$^{+}$ line image shows no feature corresponding to the peak A or B ($v_{LSR} < 35$ km s$^{-1}$), whereas it shows the E-ridge apparently. Hence, the peak A is unlikely to be a part of the E-ridge.

The peak B is seen in the SiO maps at $v_{LSR} > 30$ km s$^{-1}$. Beyond $v_{LSR} > 45$ km s$^{-1}$ the position of the peak B is shifted toward the north by 20″. In the H$^{13}$CO$^{+}$ map a clear counterpart is seen only beyond $v_{LSR} > 45$ km s$^{-1}$. It suggests that the peak B may be a double source and separable at $v_{LSR} = 45$ km s$^{-1}$. In any case, the peak B with $v_{LSR} < 45$ km s$^{-1}$ is only seen in the SiO lines.

The peak C is seen between 30 km s$^{-1} < v_{LSR} < 45$ km s$^{-1}$. The H$^{13}$CO$^{+}$ map shows its counterpart clearly. The peak C is morphologically connected to the E-ridge in $l − b − v$ space. The E-ridge and the peak C might be two main parts of G0.11−0.11.

3.2. Intensity ratio

To evaluate the morphological resemblance among the SiO lines and difference between the H$^{13}$CO$^{+}$ and SiO lines quantitatively, we estimate intensity ratios of observed lines. They are keys to determine the optical depth and/or physical conditions of the emitting gas in G0.11−0.11.

First, we estimate an intensity ratio of two SiO lines, $R_{SiO(2−1)/SiO(1−0)}$. To calculate an average value, we use an intensity correlation for all the observed points in a box assigned in $l − b − v$ space for each feature. To remove the difference in resolution due to different beam size at the three lines, we reduce the resolution to be 45″ by appropriate gaussian convolution. We found the ratios of SiO $J = 2 − 1$ line to SiO $J = 1 − 0$ line to be 0.9–1.0 for the E-ridge and the three peaks, and also found no significant difference of the ratios among the regions in the cloud.

We also estimated the line intensity ratios of H$^{13}$CO$^{+}$ $J = 1 − 0$ to SiO $J = 1 − 0$, and found them to be uniform in each feature, although they differ significantly between northern and southern parts of G0.11−0.11. For the E-ridge and the peak C, they are 0.5. For the peaks A and B, they are about 0.2 or smaller, although the S/N is poor.

4. Discussion

4.1. Column density and mass of the cloud

The H$^{13}$CO$^{+}$ $J = 1 − 0$ line is expected to be optically thin, because of its small abundance. We can check it from the H$^{13}$CO$^{+}$ $J = 1 − 0$ intensity compared with the CS $J = 2 − 1$ intensity. We should note that, since the excitation parameters of both the lines are similar, their intensity ratio ought not to be a strong function of the physical conditions of the gas; accordingly the only causes of variation in this ratio must be variations in either the relative abundances of the species or in their relative optical depth. Using an H$^{13}$CO$^{+}$ abundance of 10$^{-10}$ and a CS abundance of 10$^{-8}$ [5, 6] together with excitation parameters of the lines, the expected intensity ratio of
H^{13}CO\(^+\) \(J = 1 - 0\) to CS \(J = 2 - 1\) is about \(6 \times 10^{-3}\), if both lines are optically thin. Using published CS data [2], the line intensity ratio of the H^{13}CO\(^+\) \(J = 1 - 0\) to the CS \(J = 2 - 1\) is calculated to be 0.12–0.14 in the southern part of G0.11–0.11. It follows that the CS line in this locality must be optically thick, whereas the optical depth of H^{13}CO\(^+\) \(J = 1 - 0\) is about 0.1. In the northern part of the cloud, the ratio is about 0.05 or smaller and the H^{13}CO\(^+\) \(J = 1 - 0\) line is therefore optically thin.

Then, we estimate column density of the southern part of G0.11–0.11 and molecular mass of the whole cloud from H^{13}CO\(^+\) \(J = 1 - 0\) intensity under the condition of local thermal equilibrium (LTE). When we assume \(T_K = 70\) K, the column density of molecular hydrogen at the E-ridge is derived to be \(N(\text{H}_2) = (6 - 7) \times 10^{23}\) cm\(^{-2}\). This corresponds to about 640–740 mag in \(A_V\) (visual extinction) at the typical gas-to-dust ratio expected for dense clouds, and about 80–90 mag and 10–12 mag in \(A_K\) and \(A_{25\mu m}\) (extinction at 25\(\mu m\)), respectively [7]. Similar values are obtained for peak C. This large \(A_{25\mu m}\) is consistent with the fact that G0.11–0.11 is observed as a shadow in an infrared map with MSX [8]. The shadow has the similar spatial extension on the sky to that in H^{13}CO\(^+\) \(J = 1 - 0\).

In submillimeter continuum map we can find the counterpart of G0.11–0.11, although it is less prominent than major submillimeter features [9]. Using the same conversion from gas column density to submillimeter brightness as theirs, \(N(\text{H}_2) = 6 \times 10^{23}\) cm\(^{-2}\) corresponds to 20 Jy 8\(^\prime\)-beam\(^{-1}\) at 450 \(\mu m\) and 8 Jy 15\(^\prime\)-beam\(^{-1}\) at 850 \(\mu m\), respectively. The maps with SCUBA [9] show about 15–20 Jy beam\(^{-1}\) at 450 \(\mu m\) and 3–4 Jy beam\(^{-1}\) at 850 \(\mu m\), respectively. The estimated values are consistent, because both estimations are based on assumptions with some uncertainty. The gas-to-dust mass ratio may be reduced in the cloud, because strong thermal SiO line of the cloud suggests dust evaporation. The molecular abundance of H^{13}CO\(^+\) may be smaller than the value we assumed. Moreover, inhomogeneity in the cloud may affect the conversion factors from the observable values to the true mass of the cloud.

The estimated column density of G0.11–0.11 is one of the largest ever observed even in the Galactic Center region. For several X-ray sources in the Galactic Center region, total hydrogen column densities were estimated to be \(N(\text{H}_2) \leq (1 - 3) \times 10^{23}\) cm\(^{-2}\) [10, 11]. The cloud G0.11–0.11 shows a larger column density by at least factor of 5 than the ordinary environments in the Galactic Center region. It is extraordinarily large, being comparable only with Sgr B2, which is the most massive cloud in the Galaxy.

Other than G0.11–0.11, many dark features in the MSX map are found in the Galactic Center region. They are called as the MSX dark clouds [8]. Some of them were also observed in the H\(_2\)CO line [12]. Typical column densities for MSX dark clouds are estimated to be \(N(\text{H}_2) = 10^{23–25}\) cm\(^{-2}\). Our estimated column density of G0.11–0.11 is as large as the typical MSX dark clouds; n.b., G0.11–0.11 itself was not observed.

4.2. The SiO emitting clump and its structure

The intensity ratio of the two SiO lines, \(R_{\text{SiO}(2-1)/\text{SiO}(1-0)}\) is about 0.9–1.0 for all the features in G0.11–0.11 (Section 3.2). This value implies two possibilities; one is that the both the SiO lines are optically thick, and the other is that the both the lines are optically thin and the density of molecular hydrogen in the SiO-emitting gas is \(10^{3.7–3.8}\) cm\(^{-3}\). However, the latter case is unlikely for the following two reasons. If the hydrogen density were \(10^7\) cm\(^{-3}\), the CS lines would be optically thin. But our estimation (Section 4.1), as well as the previous estimation [2], shows that the CS line is (at least moderately) optically thick.

Because the observed antenna temperature at the SiO line is much lower than the expected gas kinetic temperature, the beam filling factor must be smaller than unity, i.e. the telescope beam is not filled with the emitting surface. Hence, we should employ a “clumpy model” ([13]) to consider a physical state of G0.11–0.11. Using the “clumpy model”, the observed line-intensity ratio depends on the opacity of the emitting clumps, and the observed antenna temperature is
reduced by the beam filling factor.

Using “clumpy model” and optically thick line, we can roughly estimate some parameters of a clump. We find that the mainbeam brightness temperatures of most features in G0.11−0.11 are $T_{MB} = 1−2K$. When $T_K = 70K$, the typical beam filling factor is 0.02. Because G0.11−0.11 does not show a discrete clump with $35''$ beam, there must be 10 or more clumps in a beam. Thus the diameter of a clump is smaller than $1.5''$ or 0.06 pc. The averaged gas density in a clump is then estimated to be higher than $2 \times 10^8 cm^{-3}$.

In this case a clump may be unstable, because the free fall time of the clump is much shorter than the sound crossing time. However, it can be stable when the size of a clump is much smaller. Given a beam averaged column density and beam filling factor, the free fall time is proportional to square root of the clump size. On the other hand, given a gas temperature, the sound crossing time is proportional to the size. Therefore, the clump can be stable when the size is smaller than $4 \times 10^{-4}$ pc for our estimated values. Note that the critical size may be much larger, if the clump is supported by magnetic field.

Large opacity even in dense gas tracers and large extinction even in mid-infrared suggest that the cooling time may be longer than cores in starforming regions in the Galactic disk region. Using virial mass analysis, Sawada et al. show that molecular clouds in the Galactic Center region are under high pressure as $nT_K = 10^5 K cm^{-3}$ [14]. By this external pressure, emitting clumps in G0.11−0.11 may be compressed.

From our observations, G0.11−0.11 is found to be likely composed from many hot and dense clumps, which can be hardly cooled down because of large extinction even in infrared. This condition is greatly different from that of starforming clouds in the Galactic disk region. Under such condition, star formation should be much different. This may be a reason why a dense cluster of massive stars is seen only in the Galactic Center region. Although G0.11−0.11 is a good site to investigate this speculation, high resolution observations in rarer molecules such as CS isotopes are required to unveil optically thick clump.

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