THERMAL SiO AND H$^{13}$CO$^+$ LINE OBSERVATIONS OF THE DENSE MOLECULAR CLOUD G0.11−0.11 IN THE GALACTIC CENTER REGION$^1$

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Received 2004 December 26; accepted 2005 September 7

ABSTRACT
We obtained the first view in H$^{13}$CO$^+ J = 1−0$ and a high-resolution map in thermal SiO lines of G0.11−0.11, which is a molecular cloud situated between the Galactic Center radio arc and Sgr A. From a comparison with previous line observations, we found that the H$^{13}$CO$^+ J = 1−0$ line is optically thin, whereas the thermal SiO lines are optically thick. The line intensity in H$^{13}$CO$^+ J = 1−0$ shows that the cloud has a large column density, up to $N$(H$_2$) = $(6−7) \times 10^{23}$ cm$^{-2}$, which corresponds to about 640−740 mag in $A_V$ or 10−12 mag in $A_{25 \mu m}$. The estimated column density is the largest known of any even in the Galactic center region. We conclude from the intensity ratio of SiO $J = 1−0$ to CS $J = 1−0$ that emitting gas is highly inhomogeneous for SiO abundance on a scale smaller than the beam width $\sim 35''$.

Subject headings: Galaxy: center — ISM: general — ISM: structure

1. INTRODUCTION

Recent infrared observations have revealed the existence of a population of dense bright-star clusters in the Galactic center region (e.g., Figer et al. 2002), such as the Arches cluster and the Quintuplet cluster. Although these clusters must be made from molecular clouds in the Galactic center region, it remains unclear what modifies the star formation process to form such extremely massive stars. Further detailed observations of dense molecular clouds in the Galactic center region may provide a key to understanding the physical properties of the clouds and their relationship to this star-forming mechanism.

Large-scale surveys in molecular lines have revealed that molecular clouds in the central $\sim 100$ 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 the density of most molecular clouds there is over $10^4$ cm$^{-3}$ (Tsuboi et al. 1999). Moreover, the multiline observations show that even the CO-emitting region (or outer envelope) of a typical Galactic center molecular cloud is under high pressure at $nT_K = 10^5$ K cm$^{-3}$ (Oka et al. 1998; Sawada et al. 2001).

Among dense molecular clouds in the Galactic center region, the molecular cloud G0.11−0.11$^2$ is unique and one of the most interesting objects. It is located between Sgr A and the Galactic center arc (GCA). The NRO CS survey (Tsuboi et al. 1999) shows that G0.11−0.11 is well separated in $l-b-v$ space from the main ridge of the CS emission, which is the central disk of molecular gas in the Galactic center. The CS observations reveal that G0.11−0.11 has a large molecular mass and large velocity width at the eastern$^3$ and western edges of the cloud. The eastern edge appears to have an interaction with the GCA (Tsuboi et al. 1997). G0.11−0.11 is bright at the X-ray fluorescent iron line (Yusef-Zadeh et al. 2002), which suggests that dense gas in the cloud reflects X-rays from an intense source.

The morphologies of G0.11−0.11 in the CS and CO lines are similar. These lines are presumably optically thick at the surface of the cloud. To obtain the physical properties of the cloud, observations in an optically thin line are required. The H$^{13}$CO$^+$ ($J = 1−0$) line should be suitable because of its very low abundance. Here we present the first view in an H$^{13}$CO$^+$ line of G0.11−0.11, exploring the molecular gas distribution in the cloud. 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 of hot and shocked regions because this molecule is in a gas phase only in a high-temperature environment (Ziurys et al. 1989). For example, thermal SiO emission is detected in bipolar flow sources and in shocked shells of supernova remnants. Martin-Pintado et al. (1997) surveyed the Galactic center region in the thermal SiO line. However, they observed only half the extent of G0.11−0.11, and with poor angular resolution. We have now made observations of G0.11−0.11 in these

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$^1$ This work was carried out under the common-use observation program at Nobeyama Radio Observatory (NRO).

$^2$ The cloud is referred to as Tsuboi’s shell in the NRO 45 m CO survey (Oka et al. 2001), as G0.11−0.11 in Reich (2003), and as the TUH shell in Yusef-Zadeh et al. (2002).

$^3$ In this paper, all directions on the sky are in terms of Galactic coordinates.
lines using the Nobeyama 45 m telescope with much higher resolution.

2. OBSERVATIONS

We observed G0.11 − 0.11 in 2002 April, using the Nobeyama 45 m telescope, simultaneously observing at the spectral lines of H\(^{13}\)CO\(^+\) \(J = 1-0\), \(v = 0\), SiO \(J = 2-1\), \(v = 0\), and H\(^{13}\)CO\(^+\) \(J = 1-0\) and (d) a schematic chart of main features. The velocity range is 15 km s\(^{-1}\) \(\geq V_{\text{LSR}} \leq 45\) km s\(^{-1}\). The FWHM beam sizes are adjusted to 45\(^{\prime}\), shown in (d). The intensity scale is in integrated main-beam brightness temperature, \(T_{\text{MB}}\). Both the first contour level and the contour interval are 2 K km s\(^{-1}\) for (a–c). The gray scale in (d) is the same map as in (a).

![Integrated intensity maps of G0.11 − 0.11](image)

**Fig. 1.** Integrated intensity maps of G0.11 − 0.11 in (a) SiO \(J = 1-0\), \(v = 0\), (b) SiO \(J = 2-1\), \(v = 0\), and (c) H\(^{13}\)CO\(^+\) \(J = 1-0\) and (d) a schematic chart of main features. The velocity range is 15 km s\(^{-1}\) \(\geq V_{\text{LSR}} \leq 45\) km s\(^{-1}\). The FWHM beam sizes are adjusted to 45\(^{\prime}\), shown in (d). The intensity scale is in integrated main-beam brightness temperature, \(T_{\text{MB}}\). Both the first contour level and the contour interval are 2 K km s\(^{-1}\) for (a–c). The gray scale in (d) is the same map as in (a).

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 km s\(^{-1}\) \(\geq V_{\text{LSR}} \leq 45\) km s\(^{-1}\). The spatial resolutions are adjusted to 45\(^{\prime}\) by applying a Gaussian convolution. A shell-like molecular cloud is seen in all three lines. The appearance in the SiO lines resembles that in the CS \(J = 1-0\) line (see Fig. 1 of Tsuboi et al. 1997).

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 in the southern half of the cloud, although the cloud seems to extend beyond \(b \leq -0^\circ 6\)’ in the SiO and CS images. In the H\(^{13}\)CO\(^+\) \(J = 1-0\) line, the integrated intensity in \(b \leq -0^\circ 6\)’ is 80% of the total intensity of the whole cloud.
cloud, which is integrated over $0'5' \leq l \leq 0'9', -0'9'20'' \leq b \leq -0'4'20''$. These discrepancies are presumably due to the difference in optical depths between the SiO and H$^{13}$CO$^+$ lines (see details in § 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 a significant difference in column density below and above a front at $b = -0'6'$.

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 three lines. We dub it the E ridge hereafter (Fig. 1, solid line). At $l = 0'7'$, it extends from $b = -0'6'$ to $-0'9'$ perpendicular to the Galactic plane. On the northern end of the E ridge, a peak is seen in both SiO lines at $l = 0'8', b = -0'5'20''$ (hereafter peak A). 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.

Figures 2, 3, and 4 show the channel maps of the H$^{13}$CO$^+ J = 1$–$0$ line and the two SiO lines with a velocity interval of 5 km s$^{-1}$. The FWHM in these figures is increased to 45'' by Gaussian smoothing. The typical rms noise levels in $T_{MB}$ for H$^{13}$CO$^+ J = 1$–$0$, SiO $J = 1$–$0$, and $J = 2$–$1$ lines are 0.042, 0.050, and 0.042 K, respectively.

The E ridge is seen in the SiO channel maps in the range $15 \text{ km s}^{-1} < v_{LSR} < 50 \text{ km s}^{-1}$. A corresponding feature is also seen in the CS line (Fig. 2 in Tsuboi et al. 1997). 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

![Fig. 2.—Channel map of intensity in H$^{13}$CO$^+ J = 1$–$0$. The data are smoothed by a Gaussian to 45'' resolution. The intensity scale is in main-beam brightness temperature, $T_{MB}$. Both the first contour level and contour interval are 0.1 K in all panels.](image1)

![Fig. 3.—Same as Fig. 2 but for SiO $J = 1$–$0$.](image2)
probably not very strong, if it exists, because the E ridge is not the most prominent feature in the SiO image.

In the H13CO+ $J = 1-0$ map the E ridge is also distinguishable but less prominent than in the SiO lines, and very weak at $b < -0.6'$. The velocity structures of the E ridge in the SiO and H13CO+ lines are similar at $v_{LSR} \leq 40$ km s$^{-1}$. The SiO emission is extended beyond $v_{LSR} < 40$ km s$^{-1}$, but the H13CO+ $J = 1-0$ emission is not. We note that this extension of the E ridge in the SiO emission connects at $v_{LSR} > 45$ km s$^{-1}$ to the ridge extending at $b = -0.5'$, which goes through peak B (see Fig. 5).

Peak A is seen in the SiO maps in the range $10$ km s$^{-1} < v_{LSR} < 35$ km s$^{-1}$. At the high-redshift end, peak A is merged into the ridge along the Galactic plane through peak B. In the SiO line images, peak A appears to be somehow connected with the E ridge. However, the H13CO+ line image shows no feature corresponding to peak A or B ($v_{LSR} < 35$ km s$^{-1}$), whereas it seems to show the E ridge. Hence, peak A is unlikely to be a part of the E ridge.

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 peak B is shifted northward by 20'. In the H13CO+ map a clear counterpart is seen only beyond $v_{LSR} > 45$ km s$^{-1}$. This suggests that peak B may be a double source and separable at $v_{LSR} = 45$ km s$^{-1}$. In any case, peak B with $v_{LSR} < 45$ km s$^{-1}$ is only seen in the SiO lines.

Peak C is seen in the range $30$ km s$^{-1} < v_{LSR} < 45$ km s$^{-1}$. The H13CO+ map shows its counterpart clearly. Peak C is morphologically connected to the E ridge in $l-b-v$ space. The E ridge and peak C might be two main parts of G0.11–0.11.

Another prominent ridge with $v > 45$ km s$^{-1}$ at $b = -0.5'$ parallel to the Galactic plane is seen in all the observed lines. The large-scale velocity structure observed in CS (Tsuboi et al. 1999) suggests that this ridge is a blueshifted wing of the main ridge of the Galaxy through the whole Galactic center region. Therefore, we do not discuss this feature in this paper.

### 3.2. Intensity Ratio

To evaluate the morphological resemblance among the SiO lines and the difference between the H13CO+ and SiO lines quantitatively, we estimate the intensity ratios of the observed lines, which are keys to determining 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 45' by an appropriate Gaussian convolution. We found the ratios of the SiO $J = 2-1$ line to the 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 in the ratios among the regions in the cloud.

We also estimated the line intensity ratios of H13CO+ $J = 1-0$ to SiO $J = 1-0$ and found them to be uniform in each feature, although they differ significantly between the northern and southern parts of G0.11–0.11. For the E ridge and peak C, they are 0.5.
For peaks A and B, they are about 0.2 or smaller, although the signal-to-noise ratio is poor.

4. DISCUSSION

4.1. Column Density and Mass of the Cloud

The H13CO+ J = 1−0 line is expected to be optically thin, because of its small abundance. We can check it by comparing the H13CO+ J = 1−0 intensity with the CS J = 2−1 intensity. We should note that since the excitation parameters of both 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 either in the relative abundances of the species or in their relative optical depth. Using an H13CO+ abundance of 10−10 and a CS abundance of 10−8 (García-Burillo et al. 2000; Irvine et al. 1987), together with the excitation parameters of the lines, the expected intensity ratio of H13CO+ J = 1−0 to CS J = 2−1 is about 6 × 10−3 if both lines are optically thin. Using CS observations by Tsuboi et al. (1997), the line intensity ratio of H13CO+ J = 1−0 to 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 H13CO+ J = 1−0 is about 0.1. In the northern part of the cloud, the ratio is about 0.05 or smaller and the H13CO+ J = 1−0 line is therefore optically thin.

Then we estimate the column density of the southern part of G0.11−0.11 and the molecular mass of the whole cloud from the H13CO+ J = 1−0 intensity under the condition of local thermal equilibrium (LTE). In this case, we need to know the kinetic temperature (TK) of the emitting gas. The kinetic temperature of molecular gas in the Galactic center region is controversial. In the Galactic center region, TK of dense molecular clouds is estimated to be 60–80 K or hotter (Morris et al. 1983; Hüttemeister et al. 1993; Lis et al. 2001). Here we assume TK = 70 K. Thus, the column density of molecular hydrogen at the E ridge is derived to be N(H2) = (6.7) × 1023 cm−2. This corresponds to about 640–740 mag in Aν (visual extinction) at the typical gas-to-dust ratio expected for dense clouds, and about 80–90 and 10–12 mag in Aν and A25μm (extinction at 25 μm), respectively (Mathis 2000). Similar values are obtained for peak C. This large A25μm is consistent with the fact that G0.11−0.11 is observed as a shadow in an infrared map with the Midcourse Space Experiment (MSX; Egan et al. 1998). The shadow has a spatial extension on the sky similar to that in H13CO+ J = 1−0.

In the submillimeter continuum map we can find the counterpart of G0.11−0.11, although it is less prominent than major submillimeter features (Pierce-Price et al. 2000). Using the same conversion from gas column density to submillimeter brightness as Pierce-Price et al. (2000), N(H2) = 6 × 1023 cm−2 corresponds to 20 Jy beam−1 at 450 μm with an 8 K beam and 8 Jy beam−1 at 850 μm with a 15 K beam. The maps with SCUBA (Submillimeter Common-User Bolometric Array; Pierce-Price et al. 2000) show about 15–20 Jy beam−1 at 450 μm and 3–4 Jy beam−1 at 850 μm. The estimated values are consistent because both estimates are based on assumptions with some uncertainty. The gas-to-dust mass ratio may be reduced in the cloud because the strong thermal SiO line of the cloud suggests dust evaporation. The molecular abundance of H13CO+ may be smaller than the value that 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(H) = (1–3) × 1025 cm−2 (Sakano et al. 1999; Sakano 2000). The cloud G0.11−0.11 shows a column density larger by at least a factor of 5 than the ordinary environments in the Galactic center region. It is extraordinarily large, being comparable only to 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 the MSX dark clouds (Egan et al. 1998). Some of them have also been observed in the H2CO line (Carey et al. 1998). Typical column densities for MSX dark clouds are estimated to be N(H2) = 1021–1025 cm−2. Our estimated column density of G0.11−0.11 is as large as that of the typical MSX dark clouds; n.b., Carey et al. (1998) did not observe G0.11−0.11.

Finally, we estimated the molecular mass of G0.11−0.11 to be 6.3 × 105 M⊙ from the integrated intensity in the H13CO+ J = 1−0 line for T_{ex} = 70 K. This is consistent with the previous estimate, based on the CS J = 1−0 line (3.6 × 105 M⊙; Tsuboi et al. 1997). We should note that the previous estimate was made on the assumption that the CS J = 1−0 line is moderately opaque (τ ∼ 1) and should therefore have a large uncertainty.

4.2. The SiO-emitting Clump and its Structure

The intensity ratio of the two SiO lines, R_{SiO(2−1)/SiO(1−0)}, is about 0.9–1.0 for all the features in G0.11−0.11 (§ 3.2). This value implies two possibilities; one is that both SiO lines are optically thick, and the other is that both lines are optically thin and the density of the molecular hydrogen in the SiO-emitting gas is 10^{3.7}–10^{3.8} cm−3. However, the latter case is unlikely for the following two reasons. If the hydrogen density were 10^{3.7}–10^{3.8} cm−3, the CS lines would be optically thin. But our estimate (§ 4.1), as well as the previous estimate (Tsuboi et al. 1997), shows that the CS line is (at least moderately) optically thick. Moreover, uniformity of the SiO line intensity ratio over G0.11−0.11 in the optically thin case requires uniformity of the gas density over a scale of several parsecs in a cloud that, on the contrary, is known to have a complicated morphology. Therefore, we conclude the former case to be likely: both SiO lines are optically thick in G0.11−0.11.

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 by the emitting surface. Hence, we should employ a “clumpy model” (Snell et al. 1984) to consider the 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 the clumpy model and an optically thick line, we can roughly estimate some clump parameters. In Figure 3, we find that the main-beam brightness temperatures of most features in G0.11−0.11 are T_{MB} = 1–2 K. When TK = 70 K, the typical beam filling factor is 0.02. Because G0.11−0.11 does not show a discrete clump with a 35 K beam, there must be 10 or more clumps in a beam. Thus, the clump diameter is smaller than 15″, or 0.06 pc. The averaged gas density in a clump is then estimated to be higher than 2 × 10^4 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 the clump is much smaller. Given a beam averaged column density and beam filling factor, the free-fall time is proportional to the square root of the clump size. On the other hand, given a gas temperature, the
The ratio of the projected area of the SiO-emitting part to that of the CS-emitting part is the same as the value of the intensity ratio of these lines because both lines are optically thick. We find that the intensity ratio of SiO $J = 1-0$ to CS $J = 1-0$ is uniform over the cloud. This uniformity implies that the ratio of the projected areas in a clump is uniform over the cloud. Thus, the abundance gradient of SiO in the emitting clump is presumably due to a mechanism on a scale much larger than the whole cloud. Consequently, clump internal structure should be the same over the whole cloud. In this case, it is a reasonable assumption that the emitting clump is spherically symmetric.

In the case of a spherically symmetric clump, the SiO-emitting part should be at a smaller radius than the CS-emitting part. It follows that the emitting clump is hotter in the innermost part because the SiO abundance is believed to increase in hot (e.g., shock heated) gas. Even in this case, our discussion is valid, although our model is inconsistent with the simplest clumpy model; the main-beam brightness temperature of an optically thick clump is the same when the product of the surface area and the actual brightness temperature is the same.

The large opacity even in dense gas tracers and large extinction even in the mid-infrared suggest that the cooling time may be longer than that in cores in star-forming regions in the Galactic disk region. Using virial mass analysis, Sawada et al. (2001) show that molecular clouds in the Galactic center region are under a high pressure of $nT_K = 10^5$ K cm$^{-3}$. Emitting clumps in G0.11–0.11 may be compressed by this external pressure.

From our observations, G0.11–0.11 is found to be likely composed of many hot and dense clumps, which can hardly be cooled down because of large extinction even in the infrared. This condition is greatly different from that of star-forming clouds in the Galactic disk region. Under such conditions, star formation should be very 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 for investigating this speculation, high-resolution observations in rarer molecules such as CS isotopes are required to unveil optically thick clumps.

Facilities: No: 45 m

The authors express their thanks to J. M. Stewart for his linguistic help. The authors thank the referee for suggestions that improved the paper.

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The clumpy model can explain why the intensity ratios of the optically thin (H$^{13}$CO$^+$ $J = 1-0$) to thick (CS and SiO) lines are not significantly different in the southern half of the cloud. In the clumpy model, the shape of a line profile observed with a finite beam size is given only by the distribution of the emitting clumps in velocity space. In the case of a small beam filling factor, each emitting clump does not screen other clumps even if the line is optically thick. Therefore, optically thick lines show almost the same profile shape as optically thin lines.

The CS line intensity observed by Tsuboi et al. (1997) shows that the main-beam brightness temperature in the CS $J = 1-0$ line is brighter than that in the SiO lines by a factor of 3, although both lines are optically thick in G0.11–0.11. This means that the beam filling factor at the SiO line must be smaller than that at the CS line. However, in the case of the simplest clumpy model, in which every emitting clump is assumed to be isothermal and uniform in density, the line intensity ratio of SiO to CS is expected to be unity because the excitation parameters of SiO and CS are very close. To resolve this discrepancy, we deduce that the emitting gas clump has a steep abundance gradient in SiO and that the typical size of an optically thick surface (or beam filling factor) that emits the SiO line is much smaller than the corresponding emission surface of the CS line. With the same clump temperature and density, the optical depth in the SiO lines can vary, depending on the SiO abundance. In fact, the observed SiO abundance, $X$(SiO), differs by several orders of magnitude for molecular gas in the Galactic disk region: e.g., $X$(SiO) $\approx 10^{-12}$ for quiescent dark clouds (Ziurys et al. 1989) and $X$(SiO) $= 10^{-7}$ to $10^{-8}$ in bipolar outflows of star-forming regions (Martin-Pintado et al. 1992; Schilke et al. 1997; Gueth et al. 1998).

The ratio of the projected area of the SiO-emitting part to that of the CS-emitting part is the same as the value of the intensity ratio of these lines because both lines are optically thick. We find that the intensity ratio of SiO $J = 1-0$ to CS $J = 1-0$ is uniform over the cloud. This uniformity implies that the ratio of the sound crossing time is proportional to the size. Therefore, the clump can be stable when the size is smaller than $4 \times 10^{-5}$ pc for our estimated values. Note that the critical size may be much larger if the clump is supported by magnetic field.

The clumpy model can also explain why the intensity ratios of the optically thin (H$^{13}$CO$^+$ $J = 1-0$) to thick (CS and SiO) lines are not significantly different in the southern half of the cloud. In the clumpy model, the shape of a line profile observed with a finite beam size is given only by the distribution of the emitting clumps in velocity space. In the case of a small beam filling factor, each emitting clump does not screen other clumps even if the line is optically thick. Therefore, optically thick lines show almost the same profile shape as optically thin lines.

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