CO CORE CANDIDATES IN THE GEMINI MOLECULAR CLOUD

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ABSTRACT

We present observations of a 4 square degree area toward the Gemini cloud obtained using J = 1–0 transitions of 12CO, 13CO, and C18O. No C18O emission was detected. This region is composed of 36 core candidates of 12CO. These core candidates have characteristic diameters of 0.25 pc, excitation temperatures of 7.9 K, line widths of 0.54 km s\(^{-1}\), and mean masses of 1.4 \(M_\odot\). They are likely to be starless core candidates or transient structures, which probably disperse after \(~\sim\)10\(^5\) years.

Key words: ISM: kinematics and dynamics – ISM: molecules – stars: formation

1. INTRODUCTION

Over the past several decades, relative to larger molecular gas surveys in the Galactic plane, very few similar systemic studies were toward high galactic latitudes. The Columbia gas surveys in the Galactic plane, very few similar systemic studies were toward high galactic latitudes. The Columbia survey conducted a large area survey up to a latitude \(b = \pm 35^\circ\) (Dame et al. 2001), however, its relatively poor angular resolution \(\sim 8\) is much larger than a typical core.

The study of high-latitude molecular gas was active in the 1980s and 1990s. High-latitude molecular gas was researched in various molecules, such as CO and its isotopes, NH3, H2CO (Magnani et al. 1988; Turner 1993a, 1993b), etc. In terms of its physical conditions, high-latitude molecular gas is similar to the diffuse cloud in the galactic plane, and in terms of its chemical abundance, it is similar to the cold dark cloud in the galactic plane (Turner et al. 1989). High-latitude molecular gas also was believed to be in the vicinity of the Sun (Magnani et al. 1985).

We are carrying out a large-scale survey toward high-latitude molecular gas in the northern sky with a resolution of \(\sim 50\)'. Our aims are to understand the structure, stability, and physical conditions of molecular cores in the local area between longitudes \(l \sim -10^\circ\) to \(280^\circ\) and \(b \sim \pm 5^\circ\). Here we report our observations of the Gemini molecular cloud, which is centered at \((l, b) = (200^\circ, 20^\circ)\) and was also observed by the Columbia survey (Dame et al. 2001), however, no other researchers have made further efforts to study this region in detail. The Gemini molecular cloud is usually associated with “Gem OB 1,” however, it has nothing to do with Gem OB 1 since its \(V_{lsr}\) is much less than that of Gem OB 1. It is actually located to the northeast of Gem OB 1 with an angular distance of about 12°. The distances to the two clouds also are markedly different. With a resolution of \(51\)", which is about a factor of 10 higher than the Columbia survey, we are able to distinguish a molecular core with a scale of about 0.10 pc at a distance of 400 pc, which is estimated by combining four ways: the distance of star in the line of sight of the Gemini molecular cloud, the distance estimated by the scale height of gas, the distances of nearby molecular clouds, and the distance estimated by the interstellar extinction distribution. See details in Section 3.2.

2. OBSERVATIONS AND DATA REDUCTION

We observed 12CO (1–0), 13CO (1–0), and C18O (1–0) with the Purple Mountain Observatory Delingha (PMODLH) 13.7 m telescope from 2014 May 5 to June 21 and December 18 to 30. These three lines were simultaneously observed with the nine-beam superconducting array receiver working in sideband separation mode and using the fast Fourier transform spectrometer (Shan et al. 2012).

Our observations were made in 16 cells of dimensions 30'x 30', which covered an area of 4 square degrees (248 pc\(^2\) at distance of 400 pc). The cells were mapped using the on-the-fly observation mode with the standard chopper wheel method for calibration (Penzias & Burrus 1973). In this mode, the telescope beam scanned along lines of galactic longitude and galactic latitude at a constant rate of 50'' s\(^{-1}\), and the receiver records spectra every 0.3 s. Each cell was scanned in both the galactic longitude and the galactic latitude directions to reduce the fluctuation of noise perpendicular to the scanning direction. The typical system temperature \((T_A^{*})\) during observations was \(\sim 250\) K for 12CO and \(\sim 160\) K for 13CO and C18O. Finally, we calibrated the antenna temperature \((T_A)\) to the main beam temperature \((T_{mb})\) with a main beam efficiency \((\eta_{mb})\) of 46% for 12CO and 51% for 13CO and C18O. A summary of the observation parameters is listed in Table 1.

3. RESULT

3.1. General Distribution

Figure 1 shows the distribution of 12CO emission in the Gemini molecular cloud. The strongest emission is located at \((l, b) = (200^\circ, 26^\circ, 57^\circ)\) and \((l, b) = (200^\circ, 63^\circ, 75^\circ)\) with integrated intensities of 10.7 and 10.5 K km s\(^{-1}\), respectively. Similarly, Figure 2 presents an integrated intensity map of 13CO. The strongest emission is located at \((l, b) = (199^\circ, 55^\circ, 88^\circ)\) and \((l, b) = (199^\circ, 95^\circ, 78^\circ)\) with integrated intensities of 1.1 and 1.0 K km s\(^{-1}\), respectively. The positions of the emission peaks of both lines do not exactly match.
diffuse. Strong emission is only concentrated at several small locations. In the 12CO emission, clearly there are some filamentary structures that contain a few cores, while the 13CO emission is largely composed of a separate, individual core. No C18O emission was detected in a mean rms noise level of 0.19 K. We have averaged all of the spectra together to provide a single aggregate measure of the C18O brightness over the cloud, which shows an rms of 0.01 K, and are still unable to find any C18O emissions. The reason may be that the emission of C18O is too faint to be detected, and the upper limit for average $T_R$ of C18O is 0.01 K.

Figure 3 presents the longitude–velocity map of 12CO. The longitude–velocity map of 12CO suggests that $V_{\text{lsr}}$ is confined to $(-5, 5)$ km s$^{-1}$ and mainly around $\sim 0.0$ km s$^{-1}$. A second velocity component (hereafter, velocity region 1) is centered at $\sim 2.5$ km s$^{-1}$, ranging from $l \approx 199^\circ.9$ to $l \approx 200^\circ.2$, and a third one (hereafter, velocity region 2) is centered at $\sim 1.7$ km s$^{-1}$ in the range of $l \leq 199^\circ.1$. There are large offsets from 0.0 km s$^{-1}$ in the two velocity components. In addition, we find a velocity gradient of $\sim 0.3$ km s$^{-1}$ pc$^{-1}$ in the range of $l \approx 200^\circ.0$ to $l \approx 200^\circ.7$.

At first, to make clear the velocity structure in those two velocity regions, the channel maps in Figure 4 illustrate the velocity structure of the molecular emission in regions corresponding to those two velocity regions. The left maps range from $(l, b) = (199^\circ.89, 11^\circ.70)$ to $(200^\circ.20, 12^\circ.11)$, while the right ones ranges from $(l, b) = (198^\circ.79, 12^\circ.10)$ to $(199^\circ.10, 12^\circ.71)$. Both sections correspond to velocity regions 1 and 2 in Figure 3. For ease of presentation, we refer to them as map 1 and map 2, respectively.

Map 1 shows a montage of 12CO emission distributions with velocities ranging from $-2.5$ to $5.5$ km s$^{-1}$ every $1$ km s$^{-1}$, which indicates a drastic change of morphology: no cloud component appears in more than two successive channels. Similarly, map 2 shows the montage of 12CO emission with velocities ranging from $-3.5$ to $2.5$ km s$^{-1}$ every $1$ km s$^{-1}$, which presents a velocity distribution of part of the filamentary components. This montage contains two distinct components of $V_{\text{lsr}}$ that shift from $-2.5$ to $2.5$ km s$^{-1}$. These complicated features in the velocity distributions likely indicate that the cloud consists of many components with velocities differing by $\sim 5$ km s$^{-1}$. Similar to map 1, map 2 also shows a big change in morphology; for instance, the bottom cloud components appear

| Line | $\nu_0$ (GHz) | HPBW (") | $T_{\text{sys}}$ (K) | $v_{\text{lsr}}$ (km s$^{-1}$) | $\delta v$ (km s$^{-1}$) | $T_R^*$ rms noise (K) |
|------|--------------|----------|----------------|------------------------|----------------|-------------------|
| 12CO | 115.271204   | 49 ± 2   | 220–300        | 46%                     | 0.16          | 0.28              |
| 13CO | 110.201353   | 51 ± 2   | 140–200        | 51%                     | 0.17          | 0.13              |
| C18O | 109.782183   | 51 ± 2   | 140–200        | 51%                     | 0.17          | 0.19              |
in only two channels. The big change of morphology in the channel maps may be triggered by stochastic processes between clouds such as collisions and chaotic magnetic fields, rather than ordered motions such as rotation. Furthermore, unlike map 1, map 2 shows some filamentary structures, especially in the velocity range of −1.5 to −0.5 km s\(^{-1}\) and from 0.5 to 1.5 km s\(^{-1}\). In addition, 12CO emissions seldom simultaneously appear at discontinuous channels in both maps.

We present the channel map of the entire region of the Gemini molecular cloud in Figure 5. It shows that most 12CO emissions are confined to \((-2, 2)\) km s\(^{-1}\) and indicates that the morphology in Figure 5 changes less than that in the two velocity regions shown in Figure 4.

### 3.2. Distance Estimate

In order to obtain the radius of a core candidate, denoted by \(R_{13}\) for 13CO, the mass (based on local thermodynamic equilibrium, LTE), denoted by \(M\), and the virial mass, denoted by \(M_V\), the distance to the core candidate is indispensable. Kinematic distance is a widely used distance. Because the \(V_{\text{lsr}}\) of the cloud is around 0 km s\(^{-1}\) and cannot be effectively used to estimate it, we have tried four other methods to work it out.

First, we try to find stars in the line of sight of the Gemini molecular cloud and get a Tycho 2 star—TYC 1349-01421-1—with a distance of 131 pc (Ammons et al. 2006), which is located at (07:11:05.29, +17:00:45.9) in the J2000 equatorial coordinate system. \(A_K = 0.174\) and \(A_K = 0.95A_K = 0.165\), which indicates that this star is slightly reddened and also may be a foreground star as \(A_K < 0.3\) (see, e.g., Lombardi et al. 2011).

Second, for a given cloud, the expectation value of the height above the plane is \(0.798\) \(z_s\), where \(z_s\) is the Gaussian scale of the gas and is about 75 pc, and the distance to a cloud is \(0.798 b\csc z_s\), where \(b\) is the galactic latitude (see, e.g., Magnani et al. 1985). Using this method, we estimate that the distance is around 300 pc. However, this method is generally applied to clouds with \(b \geq 25^\circ\) whereas molecular gases are mainly found in the galactic plane.

Third, the fact that the Gemini molecular cloud is centered at \(l = 200^\circ\) and the \(V_{\text{lsr}}\) is around 0 km s\(^{-1}\) indicate that this cloud could be nearby like the Taurus, Lam Ori, or California giant molecular clouds whose distances are 140, 400, and 450 pc, respectively (Juvela et al. 1997; Lang et al. 2000; Lada et al. 2009).

Lastly, we use the interstellar extinction distribution to estimate the distance to the Gemini molecular cloud. We follow the approach applied by Marshall et al. (2006) and use the stellar population synthesis model of the Galaxy constructed in Besançon (Robin et al. 2003), hereafter called the Galactic model. We identify the distance in the following steps: first, in order to closely model the 2MASS stars, we cut the modeled stars at the 2MASS completeness and at \(J, H, and H, and
$K_s$ magnitude of 9 as a lower limit, and to ensure the highest reliability we fix the faint magnitude limit of the $K_s$ band to a maximum of 12 and 16 for the other two bands; second, we remove the dwarf stars from both the observations and the model; third, we bin the simulated stars by color, and the number of stars in a bin is chosen such that the median distance of the simulated stars in each successive bin increases; and last, we put the observed stars into the same number of bins as the simulated stars, and compute the $\chi^2$ statistic:

$$\chi^2 = \sum_i \left( \frac{N_{\text{obs}} - N_{\text{mod}}}{\sqrt{N_{\text{obs}} \cdot N_{\text{mod}}}} \right)^2 (n_{\text{obs}} + n_{\text{mod}}),$$

where $N_{\text{obs}}$ and $N_{\text{mod}}$ are the total numbers of stars in the observations and model, respectively, and $n_{\text{obs}}$ and $n_{\text{mod}}$ denote the numbers of stars in a particular bin for the observations and the Galactic model, respectively. After adjusting the extinction, some stars will be beyond the completeness limit for the field whereas others, intrinsically bright, will be dim enough to be admitted into our selections of dwarf stars. We repeat the process using the adjusted stars and recompute the $\chi^2$ statistic. We then continue this process until we find a minimum in the $\chi^2$ statistic and minimize the difference in extinction between observed and modeled stars; see details in Marshall et al. (2006). Figure 6 shows the result. We only find three 2MASS sources, J07084534+1610175, J07125749+1647429, and J07104500+1755493 (where the number after the letter “J” presents the coordinates of those sources in the J2000 equatorial coordinate system), which are in the line of sight of the $^{12}$CO core candidates of the Gemini molecular cloud and have $A_K = 0.67(J - K_s)$ of 0.261, 0.526, and 0.532, respectively. The distance estimated by the 2MASS source J07084534+1610175 is $430 \pm 170$ pc, with a reliability of 0.68. However, this source has $A_K = 0.95A_K = 0.248$, which may indicate that this source may be a foreground star as $A_K < 0.3$ (see, e.g., Lombardi et al. 2011). By using the other two 2MASS sources, which are background stars, we find the distance reaches to 2.6 kpc. While both of those two 2MASS stars are about $\gtrsim 1$ mag dimmer than J07084534+1610175 and have poorer signal-to-noise ratio with a factor of $\gtrsim 3.2$.

The Tycho 2 star TYC 1349-01421-1 indicates a distance of 131 pc. The molecular gases are mainly concentrated on the galactic plane, and for molecular clouds for which $b \sim 12^\circ$, the distance should be much less than 2.6 kpc. In addition, the second method shows a distance of $\sim 300$ pc, which suggests that the cloud is $< 1$ kpc away, and the third method also indicates that the Gemini molecular cloud is a nearby cloud. On the other hand, the fourth method also has a large uncertainty. Furthermore, the CO emissions suggest an averaged column density of hydrogen of $0.7 \times 10^{21}$ cm$^{-2}$ (see details in Section 3.4.4), which indicates that extinction in the $J$ band ($A_J$) is 0.13 mag according to the relation of $N_{\text{H}_2} = 5.57 \times 10^{22} A_J$ cm$^{-2}$ mag$^{-1}$ (Vuong et al. 2003), and the $A_K \sim 0.1$ by using the extinction curve of $A_J/A_K = 0.282/0.114$ (Cardelli et al. 1989). The $A_K \sim 0.1$ suggests a distance of $\sim 120$–170 pc, and also supports the theory that the cloud is far less than 1 kpc away, but the uncertainties of this relation are the scale coefficient and extinction curve, which make it difficult to estimate errors here. The $A_K \sim 0.1$ derived from the averaged column density of hydrogen may give evidence that the source J07084534+1610175 is most likely to be a background star. Combining those factors, we therefore adopt a distance of 400 pc, and denote it by $d_{\text{obs}}$. Because the distance estimated from the first method and averaged column density of hydrogen is less than 200 pc, this distance may be overestimated. The units of any quantities dependent on distance would be multiplied by an additional factor, $d/d_{\text{ref}} = d/(400 \text{ pc})$, where $d$ is in units of pc, which is the genuine distance to the Gemini molecular cloud.

### 3.3. Core Identification

The core candidate catalog produced in this paper is created from the $^{12}$CO data cube. We define cores as overdensities in a molecular cloud that may or may not contain cores from which single or multiple stars are born. These are also known as star-forming or starless cores, respectively (Williams et al. 2000; Parsons et al. 2012).

In order to decompose the Gemini molecular cloud into cores, we looked to automated core detection programs to deal with the obtained three-dimensional FITS cube file of $^{12}$CO. In this paper, we used the CUPID (part of the STARLINK project software) clump-finding algorithm CLUMPFIND (Williams et al. 1994), which has been widely used in the literature (Moore et al. 2007; Buckle et al. 2010). Due to the intrinsic biases that are present in automated core detection routines (Schneider & Brooks 2004; Smith et al. 2008), we chose the core candidates carefully, while advising caution when performing blind cross-comparison of the properties of the core candidates measured here with those from other core detection algorithms. The CLUMPFIND algorithm first contours the data and searches for peaks in order to locate the

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4 http://starlink.eao.hawaii.edu/starlink
Figure 6. Result of distance estimation by interstellar extinction distribution. Left: $J - K_s$ vs. distance; each asterisk represents a bin from our method. Right: corresponding $J - K_s$ histogram of the model and the observations. The black line represents the 2MASS observations and the red line is the result of our method.

Table 2

Properties of the 36 Core Candidates of $^{13}$CO in the Gemini Molecular Cloud

| Core Name       | $V_{lsr}$ (km s$^{-1}$) | $\Delta V_{lsr}$ (km s$^{-1}$) | $R_{13}$ ($(d/d_{ref})$ pc) | $T_{ex}$ (K) | $\tau_{13}$ | $N_{H2}$ ($\times 10^{21}$ cm$^{-2}$) | $(d/d_{ref})$ M$_\odot$ | $(d/d_{ref})$ M$_\odot$ |
|-----------------|------------------------|-------------------------------|-----------------------------|-------------|-------------|--------------------------------|-------------------------|-------------------------|
| G198.81+12.29   | -2.32                  | 0.40                          | 0.05                        | 7.7         | 0.77        | 1.4                          | 0.3                     | 0.9                     |
| G198.87+12.22   | 1.66                   | 0.41                          | 0.11                        | 7.7         | 0.20        | 0.4                          | 0.3                     | 2.4                     |
| G198.88+12.64   | -1.83                  | 0.69                          | 0.13                        | 7.3         | 0.25        | 0.7                          | 0.7                     | 7.3                     |
| G199.04+12.13   | 1.00                   | 0.33                          | 0.07                        | 7.4         | 0.59        | 0.8                          | 0.5                     | 0.9                     |
| G199.35+11.72   | 1.66                   | 0.29                          | 0.05                        | 7.4         | 0.68        | 0.8                          | 0.1                     | 0.5                     |
| G199.51+11.81   | 0.17                   | 0.77                          | 0.18                        | 10.7        | 0.09        | 0.5                          | 1.0                     | 13.3                    |
| G199.55+11.87   | 1.49                   | 0.62                          | 0.13                        | 9.9         | 0.30        | 1.3                          | 1.3                     | 5.8                     |
| G199.57+11.57   | 1.49                   | 0.63                          | 0.11                        | 6.9         | 0.31        | 0.7                          | 0.7                     | 5.5                     |
| G199.72+11.80   | 0.17                   | 0.68                          | 0.09                        | 8.2         | 0.25        | 0.9                          | 0.7                     | 5.8                     |
| G199.74+11.87   | -0.17                  | 0.50                          | 0.15                        | 8.0         | 0.23        | 0.5                          | 0.7                     | 4.4                     |
| G199.81+12.12   | -0.83                  | 0.45                          | 0.07                        | 6.9         | 0.39        | 0.7                          | 0.3                     | 2.0                     |
| G199.84+11.09   | 0.17                   | 0.50                          | 0.18                        | 9.1         | 0.26        | 0.8                          | 1.7                     | 5.6                     |
| G199.95+11.77   | 3.98                   | 0.42                          | 0.09                        | 8.7         | 0.36        | 0.8                          | 0.7                     | 2.2                     |
| G199.97+11.89   | 3.49                   | 0.63                          | 0.07                        | 9.5         | 0.27        | 1.1                          | 0.3                     | 3.3                     |
| G199.98+12.07   | 3.32                   | 0.13                          | 0.07                        | 8.4         | 0.50        | 0.3                          | 0.1                     | 0.2                     |
| G200.01+12.07   | 2.49                   | 0.48                          | 0.07                        | 8.4         | 0.30        | 0.7                          | 0.3                     | 2.2                     |
| G200.03+11.90   | 2.99                   | 0.25                          | 0.09                        | 9.5         | 0.34        | 0.6                          | 0.3                     | 0.7                     |
| G200.14+11.90   | 0.50                   | 1.60                          | 0.25                        | 8.2         | 0.16        | 1.3                          | 5.3                     | 80.2                    |
| G200.15+12.22   | -0.33                  | 0.85                          | 0.11                        | 6.8         | 0.35        | 1.1                          | 1.0                     | 9.8                     |
| G200.18+12.37   | -0.83                  | 0.81                          | 0.18                        | 7.7         | 0.25        | 0.9                          | 2.3                     | 15.5                    |
| G200.20+11.57   | 0.00                   | 0.47                          | 0.13                        | 8.3         | 0.27        | 0.6                          | 0.7                     | 3.3                     |
| G200.22+12.16   | -1.66                  | 0.52                          | 0.11                        | 7.3         | 0.28        | 0.6                          | 0.7                     | 4.0                     |
| G200.25+12.25   | -0.33                  | 0.62                          | 0.09                        | 7.1         | 0.22        | 0.5                          | 0.3                     | 4.5                     |
| G200.26+11.57   | -0.66                  | 0.70                          | 0.11                        | 7.6         | 0.26        | 0.8                          | 0.7                     | 6.9                     |
| G200.26+12.11   | -1.16                  | 0.57                          | 0.18                        | 7.2         | 0.24        | 0.5                          | 1.0                     | 7.1                     |
| G200.29+11.53   | 0.66                   | 0.63                          | 0.05                        | 7.6         | 0.28        | 0.8                          | 0.3                     | 3.1                     |
| G200.29+11.04   | -1.00                  | 0.35                          | 0.05                        | 8.4         | 0.39        | 0.7                          | 0.1                     | 0.9                     |
| G200.31+12.21   | -1.16                  | 0.37                          | 0.11                        | 6.7         | 0.36        | 0.5                          | 0.3                     | 2.0                     |
| G200.37+11.49   | -1.33                  | 0.43                          | 0.07                        | 7.5         | 0.37        | 0.7                          | 0.3                     | 1.5                     |
| G200.42+11.77   | -0.17                  | 0.58                          | 0.20                        | 8.2         | 0.23        | 0.7                          | 2.0                     | 8.7                     |
| G200.46+11.47   | 1.00                   | 0.47                          | 0.36                        | 8.3         | 0.31        | 0.7                          | 6.9                     | 10.4                    |
| G200.47+11.98   | 0.17                   | 0.49                          | 0.36                        | 7.4         | 0.32        | 0.7                          | 5.6                     | 10.7                    |
| G200.58+11.77   | -0.33                  | 0.17                          | 0.07                        | 7.6         | 0.54        | 0.4                          | 0.1                     | 0.2                     |
| G200.61+11.76   | -1.00                  | 0.41                          | 0.09                        | 7.6         | 0.44        | 0.8                          | 0.3                     | 1.8                     |
| G200.63+11.82   | 0.50                   | 0.60                          | 0.09                        | 7.6         | 0.33        | 0.9                          | 0.3                     | 4.2                     |
| G200.69+11.77   | -0.17                  | 0.54                          | 0.09                        | 7.0         | 0.31        | 0.6                          | 0.3                     | 3.1                     |
| mean            | 0.32                   | 0.54                          | 0.12                        | 7.9         | 0.33        | 0.7                          | 1.1                     | 6.7                     |
core candidates, and then follows them down to lower intensities. To obtain as much of the emission as possible without contamination from noise, we set the parameters TLOW = 2 × rms and DELTAT = 2 × rms in $^{13}$CO, where TLOW determines the lowest level contour of a core candidate, and DELTAT represents the gap between contour levels that determines the lowest level at which to resolve merged core candidates (Williams et al. 1994). The parameters of each core candidate, including the position, velocity, size in the galactic longitude and galactic latitude directions, and one-dimensional velocity dispersions, are directly obtained using this process. Moreover, further steps were taken to ensure the detection of real cores. First, we excluded core candidates that had voxels touching the edge of the map area in order to avoid core candidates where the full extent of the emission may not have been recovered. Second, we excluded core candidates whose sizes were smaller than the beam resolution. Third, we excluded core candidates that had ratios of two main axes greater than 4. Finally, the morphology of the core candidates was checked by eye within the three-dimensional galactic-longitude–galactic-latitude velocity space to identify core candidates with meaningful structures. Using these criteria, we obtain 36 core candidates (plotted in Figure 2 and cataloged in Table 2) in the $^{13}$CO maps.

Properties of the 36 core candidates of $^{13}$CO are summarized in Table 2. The columns represent, respectively, the catalog core (candidate) name, $V_{lsr}$, the line width ($\Delta v_{13}$), i.e., the velocity component along the line of sight, which is fitted by a Gaussian profile, its radius ($R_{13}$), its excitation temperature ($T_{\text{ex}}$), the optical depth ($\tau_{13}$), the column density of molecular hydrogen ($N_{\text{H}_2}$), its LTE mass ($M$), and its virial mass ($M_{\text{vir}}$). Core candidate names also convey their location, for instance: G199.04+12.13 represents the galactic longitude 199°04 and galactic latitude 12°13. The last row in Table 2 is the mean value of each physical quantity.

### 3.4. Physical Properties

#### 3.4.1. Radius

The core candidate radii are derived from the geometric mean of the core candidate sizes in two directions, and we have made the size of the beam deconvolved from the radius measurement. Figure 7 shows the distributions of the core candidate radii in $^{13}$CO. The mean core candidate radius in $^{13}$CO is 0.12 ($d/d_{\text{dev}}$) pc, and the median core candidate radius of $^{13}$CO is 0.10 ($d/d_{\text{dev}}$) pc, which is slightly less than the mean value.

#### 3.4.2. Excitation Temperature

To obtain the excitation temperature of each core candidate, three assumptions are required. First, the core candidates are in LTE, second, the emission line used in this determination is optically thick, and third, the emission fills the beam. Assuming $T_{\text{ex}}(^{13}\text{CO}) = T_{\text{ex}}(^{12}\text{CO}) = T_{\text{ex}}$ (see, e.g., Keto & Myers 1986), we calculated the excitation temperatures of the $^{12}$CO emission using the following:

\[
T_{\text{ex}} = \frac{h\nu}{k} \ln \left( 1 + \frac{KT_{\text{ex}}(^{13}\text{CO})}{h\nu} \right) \left( \frac{1}{\exp \left( \frac{h\nu}{kT_{\text{bg}}} - 1 \right)} \right) - 1, \tag{1}
\]

where $T_{\text{ex}}$ is in units of K, $h\nu$ is the energy of a single photon emitted during the transition of $^{12}$CO ($J = 1$–0), $k$ is the Boltzmann constant, $T_{\text{ex}}(^{12}\text{CO})$ is the peak main beam temperature in units of K (for $^{12}$CO emission), and $T_{\text{bg}}$ is 2.7 K, i.e., the temperature of cosmic microwave background radiation.

Excitation temperatures of the 36 core candidates cataloged in Table 2 range from 6.7 to 10.7 K, with a mean temperature of 7.9 K. We note that the excitation temperatures may be underestimated when we consider the effects of beam dilution and CO self-absorption on the obtained observations.

#### 3.4.3. Opacity

The opacity of $^{13}$CO is given by (see, e.g., Kawamura et al. 1998):

\[
\eta_{13} \approx -\ln \left( 1 - \frac{T_{\text{ex}}(^{13}\text{CO})}{5.29 \left( \frac{5.29}{\exp \left( \frac{5.29}{T_{\text{ex}}} - 1 \right) - 0.164} \right)} \right), \tag{2}
\]

where $T_{\text{ex}}$ and $T_{\text{ex}}(^{13}\text{CO})$ (in unit of K) are given in Section 3.4.2. This formula indicates that uncertainties in the excitation temperature will directly affect the opacity. The opacities of the 36 core candidates are cataloged in Table 2. We have calculated the ratio of $T_{\text{ex}}(^{12}\text{CO})/T_{\text{ex}}(^{13}\text{CO})$ in the position of peak emission of those $^{13}$CO core candidates, and this ratio ranges from 3.1 to 7.2, with a mean ratio of 4.2. We then find that the $^{12}$CO is indeed optically thick with $\eta_{13} > 1$, and the $^{12}$CO opacity of 58.4% core candidates are larger than 5.
Figure 8. Distribution of column densities (in units of $10^{21}$ cm$^{-2}$) of molecular hydrogen. The mean and median values (in units of $10^{21}$ cm$^{-2}$) are marked in the upper-right corner.

3.4.4. Column Density

The column density of $^{13}$CO $N$($^{13}$CO) is given by (see, e.g., Kawamura et al. 1998)

$$N(^{13}\text{CO}) = 2.42 \times 10^{14} \times \frac{\tau_{13} T_{\text{ex}} \Delta v_{13}}{1 - \exp(-5.29/T_{\text{ex}})},$$

where the units of $N(^{13}\text{CO})$ are cm$^{-2}$, $T_{\text{ex}}$ is the excitation temperature of the $J = 1\rightarrow 0$ transition of $^{13}$CO in units of K. The line width $\Delta v_{13}$ is in units of km s$^{-1}$. The values of $T_{\text{ex}}$, $\tau_{13}$ and $\Delta v_{13}$ are cataloged in Table 2.

Column densities in terms of H$_2$ ($N_{H_2}$) as opposed to $^{13}$CO are determined using the abundance ratio between H$_2$ and $^{13}$CO (Magnani et al. 1985; Wilson 1999), and the value adopted here is $1.2 \times 10^{-6}$. $N_{H_2}$ of the 36 core candidates cataloged in Table 2 ranging from $3.4 \times 10^{20}$ to $1.4 \times 10^{21}$ cm$^{-2}$ with a mean value of $7.5 \times 10^{20}$ cm$^{-2}$ (see Table 2). Figure 8 shows the distribution of $N_{H_2}$. Systematic errors in the column densities derived here may arise from both their opacity and their abundance ratio.

Surface densities in units of g cm$^{-2}$ are calculated by multiplying the column densities by the mass of molecular hydrogen. Within the observed Gemini molecular hydrogen, the surface densities range from $1.5 \times 10^{-3}$ to $6.4 \times 10^{-3}$ g cm$^{-2}$, with a mean value of $3.4 \times 10^{-3}$ g cm$^{-2}$.

3.4.5. Mass

Once the density and size of a core candidate have been determined, the LTE mass ($M$, in units of $(d/d_{\text{ref}})^2 M_\odot$) of the core candidate reads

$$M = A N_{\text{CO}} \left[\frac{\mu_{H_2}}{[^{13}\text{CO}]}\right]^{1/2} M_\odot,$$

where $A = \pi (R_{13})^2$ is the area of the core candidate in units of cm$^2$, where $R_{13}$ (in units of $(d/d_{\text{ref}})$ pc) is the $^{13}$CO core candidate radius which is given in Table 2 and Section 3.4.1, $N_{\text{CO}}$ is the column density of $^{13}$CO in units of cm$^{-2}$, as given in Section 3.4.4, and the abundance ratio is again assumed as $[\text{H}_2]/[^{13}\text{CO}] \sim 1.2 \times 10^8 \cdot \mu_{H_2}$ is the mean molecular weight of gas per H$_2$ molecular ($\mu_{H_2} = 2.72$ which includes hydrogen, helium, and the isotopologues of carbon monoxide; e.g., Buckle et al. 2010) and $m_H$ is the mass of a single hydrogen atom.

The core candidate masses estimated here, which are based on the assumption of LTE, range from 0.1 to 6.9 $(d/d_{\text{ref}})^2 M_\odot$ with a mean mass of 1.1 $(d/d_{\text{ref}})^2 M_\odot$ (see Table 2). The mass error comes from the distance error and its abundance ratio. Because some CO emission is absorbed by grains, these estimates can be considered as lower limits, and an estimate of the intervening dust mass is needed to determine how much it will affect our observations. The total mass of these 36 core candidates is $38.3 (d/d_{\text{ref}})^2 M_\odot$.

To obtain the virial mass $M_V$, the radius and line width are required, and a core density profile of $\rho \propto r^{-2}$ is assumed. The virial mass $M_V$ reads:

$$M_V = 126R_{13}(\Delta v)^2,$$

where $M_V$ is the virial mass in units of $(d/d_{\text{ref}})^2 M_\odot$, $R_{13}$ is the radius in $(d/d_{\text{ref}})$ pc, and $\Delta v$ is the line width in km s$^{-1}$ (MacLaren et al. 1988). The uncertainties in the virial masses come from the measurement errors of line widths and $R_{13}$.

The virial masses derived for $^{13}$CO are about 7.0 $d_{\text{ref}} / d$ times larger than the LTE masses and have a range of 0.2–8.0 $(d/d_{\text{ref}})^2 M_\odot$. The mean virial mass is 6.7 $(d/d_{\text{ref}})^2 M_\odot$ (see Table 2).

3.4.6. $V_{\text{lsr}}$ and Line Width

The core candidate line widths increase with increasing LTE masses, however, the excitation temperatures do not appear to have this tendency. This implies that thermal motion is not the exclusive broadening mechanism due to $\sigma_{\text{thermal}} \approx (T/A)^{1/2}$ km s$^{-1}$ $T^{1/2}$ in a rough sense, where $\sigma_{\text{thermal}}$ is the thermal line width (line width broadened via pure thermal motion), $T$ is the kinetic temperature in units of K, which $\gtrsim T_{\text{ex}}$, and $A$ is the atomic mass number.

To determine the dominant broadening mechanisms, we calculate thermal line widths of tracer species in units of km s$^{-1}$ using $\sigma_{\text{thermal}} = \sqrt{kT/m}/1000$, where $k$ is the Boltzmann constant, $m$ is the mean molecular mass in units of kg, and $T$ is the kinetic temperature, which $\gtrsim T_{\text{ex}}$, in units of K. The non-thermal line width $\sigma_{\text{Non-thermal}}$ and thermal line widths of gas as a whole $\sigma_{\text{thermal}, g}$ read:

$$\sigma_{\text{Non-thermal}} = \sqrt{\sigma_{\text{ID}}^2 - \sigma_{\text{thermal}}^2} = \Delta v_{1/3} \left(8 \ln 2\right) - \sigma_{\text{thermal}}^2,$$

$$\sigma_{\text{thermal}, g}^2 = \frac{1}{1000 \sqrt{\mu m_H}},$$

where $\sigma_{\text{ID}}$ is the one-dimensional velocity dispersion in units of km s$^{-1}$, $\Delta v_{1/3}$ is the line width in units of km s$^{-1}$ (see, e.g., Myers 1983), $k$ is the Boltzmann constant, $\mu = 2.4$, $m_H$ is the mass of a single hydrogen atom in units of kg and $T$ is the kinetic temperature, which $\gtrsim T_{\text{ex}}$, in units of K. $\sigma_{\text{thermal}}$ ranges from 0.04 to 0.06 km s$^{-1}$, $\sigma_{\text{thermal}, g}$ ranges from 0.15 to 0.19 km s$^{-1}$ and the distribution of $\sigma_{\text{Non-thermal}}$ is plotted in the
Because $T \gtrsim T_{\text{ex}}$, the $\sigma_{\text{Thermal}}$ and $\sigma_{\text{Thermal},g}$ are underestimated (i.e., a lower limit) and $\sigma_{\text{Non-thermal}}$ is therefore overestimated (i.e., a upper limit).

The mean ratio of $\sigma_{\text{Non-thermal}}$ to $\sigma_{\text{Thermal},g}$ is $1.35$ (see the bottom histogram in Figure 9), which implies that the non-thermal broadening mechanism plays a dominant role in the core candidates, or to be more specific, $19\%$ (i.e., 7/36) of those are subsonic core candidates and the rest are supersonic core candidates in which the non-thermal broadening mechanism plays a dominant role.

The core candidates of high $V_{\text{lsr}}$ (greater than $2 \text{ km s}^{-1}$) and low $V_{\text{lsr}}$ (lower than $-1.5 \text{ km s}^{-1}$) in $^{13}\text{CO}$ belong to two different regions (i.e., map 1 and map 2, respectively) which are plotted in the channel maps seen in Figure 4.

The big change in morphology in the channel maps in Figure 4 implies that the velocity gradients mentioned in Section 3.1 (i.e., $0.3 \text{ km s}^{-1} \text{ pc}^{-1}$) and the large dispersion of $V_{\text{lsr}}$ of the $^{13}\text{CO}$ core candidates (i.e., $6.3 \text{ km s}^{-1}$) in the Gemini molecular cloud may be more strongly affected by stochastic processes such as collisions and chaotic magnetic fields rather than ordered motions such as rotation.

4. DISCUSSION

In this section, we will discuss the statistical properties and star formation processes occurring in the Gemini molecular cloud. There is no sharp demarcation between these two aspects. In fact, statistical properties can be regarded as tools in star formation research.

4.1. Core Candidate Mass Function

The core mass function (CMF) describes the relative frequency of cores with differing masses. CMF is commonly fitted with a basic power law $dN/dM \propto M^{-\alpha}$, where $N$ is the core candidate in each bin, $M$ is the mass, and $\alpha$ is the corresponding power index. The shape of the CMF has been seen to resemble the stellar initial mass function (IMF) that describes the relative frequency of stars with differing masses.
and virial masses and LTE masses as derived from $^{13}$CO, respectively.

The similarity between the CMF and IMF power indices is between 1.83 ± 0.12 and 1.63 ± 0.12, respectively. $\alpha_1$ and $\alpha_2$ correspond to power the index of CMF of LTE mass and viral mass as derived from $^{13}$CO, respectively.

The power-law correlations of CMF are: $dN/dM = 10^{0.57±0.04} M^{-1.83±0.07}$ (left) and $dN/dM_V = 10^{0.99±0.11} M_V^{-1.63±0.12}$ (right); see Figure 10. Note that the significance of the coefficients of $10^{0.57±0.04}$ and $10^{0.99±0.11}$ is very limited for the uncertainty in distance. Our power index (1.83 for an LTE mass and 1.63 for a virial mass derived from $^{13}$CO; see Figure 10) is between the IMF of 2.35 (e.g., Salpeter 1955) and CMF of 1.6–1.8 presented by Kramer et al. (1998) and Buckle et al. (2010).

The similarity between the CMF and IMF power indices can be simply explained by a constant star formation efficiency that is unrelated to the mass and self-similar cloud structure and based on a scenario of one-to-one transformation from cores to stars (Lada et al. 2008). In addition, a simulation by Swift & Williams (2008) suggested that the obtained IMF is similar to the input CMF even when different fragmentation modes are considered. However, the full physical meaning of the relationship between the CMF and the IMF remains unclear due to a number of complications, including: (a) completeness limitations, (b) timescales, (c) physical size scales, (d) distances, etc. (Curtis & Richer 2010; Reid et al. 2010).

4.2. Star Formation

Figure 11 shows the relationship between the virial mass $M_V$ and LTE mass $M$. The virial parameter $\alpha_V$, defined as $M_V/M$, describes the competition of internal supporting energy against the gravitational energy. Virial parameter is inversely proportional to distance, and its typical value is 7.0 ($d_{\text{ref}}/d$), and all virial parameters for the 36 core candidates in $^{13}$CO are larger than 1.9 ($d_{\text{ref}}/d$). The massive core candidates tend to have lower virial parameters. Furthermore, a linear fitting between LTE mass ($M$ in unit of $(d/d_{\text{ref}})^2 M_{\odot}$) and virial mass ($M_V$ in unit of $(d/d_{\text{ref}})^2 M_{\odot}$) is presented by Kramer et al. (2008). Understanding the relationship between the CMF and IMF can help constrain star formation models (Bate & Bonnell 2005; Reid & Wilson 2006).

Figure 10. CMF (where mass includes $M$ in units of $(d/d_{\text{ref}})^2 M_\odot$ and $M_V$ in units of $(d/d_{\text{ref}}) M_\odot$). The black star-like points are logarithmic values of the number of core candidates per unit mass against log $M$ (left) and log $M_V$ (right). $\alpha_1$ and $\alpha_2$ are 1.83 ± 0.12 and 1.63 ± 0.12, respectively. $\alpha_1$ and $\alpha_2$ correspond to power the index of CMF of LTE mass and viral mass as derived from $^{13}$CO, respectively.
unit of \((d/d_{\text{ref}}) M_\odot\) may be a good indicator of the typical virial parameter: the first-order coefficient is 4.84 \((d/d_{\text{ref}})\), as shown in Figure 11, which is slightly less than the typical virial parameter value of 7.0 \((d/d_{\text{ref}})\). However, the correlation coefficient of this linear correlation is just 0.60.

The mass relationship can also be fitted with a power law of \(M_\odot \propto M^\gamma\) (where \(M\) is in units of \((d/d_{\text{ref}})^2 M_\odot\) and \(M_{\odot}\) is in units of \((d/d_{\text{ref}}) M_\odot\)) and the result is \(M_\odot = (0.76 \pm 0.15) M_{\odot}^{0.97 \pm 0.15}\). c.c. \(= 0.85\), where c.c. is the correlation coefficient and the significance of the coefficient of 0.76 \pm 0.15 is very limited for the uncertainty of distance.

The power index value of 0.97 that we obtained is larger than the value of 0.67 in Orion B (which is gravitationally bound) reported by Ikeda & Kitamura (2009) and 0.61 in Planck cold clumps (which are gravitationally bound) presented by Liu et al. (2012) and is significantly higher than the index of pressure-confined clumps \((\alpha_V \propto M^{-2/3})\) given by Bertoldi & McKee (1992). The virial parameters are larger than 1.9, which indicates that the core candidates may be unbound.

Figure 11 also shows that the virial mass changes more dramatically in the lower end of the LTE mass than in the upper end of the LTE mass. Additionally, the ratio between the virial and LTE masses decreases as LTE mass increases.

However, the discussion of whether these core candidates are pressure-confined or not may not be necessary if such structures do not need to be long lived. We then calculate a timescale \((\tau)\) used by Larson (1981):

\[
\tau \sim 4.6 \times 10^6 \frac{R_{13}}{2 \sqrt{2 \ln 2}} \frac{d}{\sigma_{\text{lsr}} \text{yr}},
\]

where, \(R_{13}\) is in units of pc, and \(\sigma_{\text{lsr}} = \sqrt{\langle\sigma_{\text{Non-thermal}}^2 + \langle\sigma_{\text{thermal}}^2\rangle^2}\) is the overall velocity dispersion of the mean particle in the cloud, where \(\sigma_{\text{lsr}}\), \(\sigma_{\text{Non-thermal}}\), and \(\sigma_{\text{thermal}}\) are in units of km s\(^{-1}\). The typical value of \(\tau\) is about \(1.7 \times 10^5\) years, thus the Gemini molecular cloud may be a transient structure.

Cores that do not have known infrared associations are starless cores or pre-protostellar cores (Benson & Myers 1989; Ward-Thompson et al. 1994). Those cores represent a stage earlier than protostellar. We have checked the IRAS point source catalog in this region and found that no \(^{13}\)CO core candidates are associated with IRAS point sources. We also have checked the WISE 22 \(\mu\)m data, and found that only one core candidate (i.e., core candidate G200.15+12.22) is associated with WISE source J071257.49+164743.5, which has an instrumental profile-fit photometry magnitude of 9.0 mag in the 22 \(\mu\)m band. However, the columns of w4sigmpro = "null" and w4chi = 0.9, which indicate that this source is not measurable in the 22 \(\mu\)m band, where the first two letters of "w4" in each column mean band 4 with wavelength of 22 \(\mu\)m. We then conclude that all 36 \(^{13}\)CO core candidates may be starless core candidates. Nevertheless, to determine whether these core candidates are in the process of forming stars, they have already formed stars, or are even in other situations, further study is necessary.

5. SUMMARY

We presented PMODLH mapping observations for an area of 4 deg\(^2\) toward the Gemini molecular cloud centered at \(l = 200^\circ\) and \(b = 12^\circ\) in \(^{12}\)CO, \(^{13}\)CO, and \(^{18}\)O lines. The main results are summarized as follows.

1. We identified 36 core candidates in \(^{13}\)CO. Derived from \(^{13}\)CO, we yield typical radii, column densities, and LTE masses of 0.12 \((d/d_{\text{ref}})\) pc, \(7.5 \times 10^{-2}\) cm\(^{-2}\), and 1.1 \((d/d_{\text{ref}})^2 M_\odot\), respectively. We also found the mean excitation temperature of 7.9 K as derived from \(^{12}\)CO. The total LTE mass derived from these 36 core candidates in \(^{13}\)CO is 38.3 \((d/d_{\text{ref}})^2 M_\odot\).

2. The non-thermal broadening mechanism plays a dominant role in 81% (29/36) of those core candidates.

3. Velocity gradients (i.e., 0.3 km s\(^{-1}\) pc\(^{-1}\)) and large dispersions in \(V_{\text{lsr}}\) of the \(^{13}\)CO core candidates (i.e., 6.3 km s\(^{-1}\)) in the cloud may be more largely affected by stochastic processes such as collisions and chaotic magnetic fields rather than ordered motions such as rotation.

4. Two kinds of CMF are present in this paper, namely the CMF of LTE masses, and the virial masses derived from \(^{13}\)CO. Their power indices are \(\alpha_1 = 1.83\) and \(\alpha_2 = 1.63\), respectively. \(\alpha_1\) and \(\alpha_2\) are all lower than the power index (2.35) of the IMF. Moreover, the CMF of LTE mass is steeper than the CMF of the virial mass derived from \(^{13}\)CO.

5. \(^{13}\)CO core candidates in the Gemini molecular cloud are more likely unbound, and massive core candidates have lower virial parameters. All 36 core candidates are potential starless core candidates, and they also may be transient structures.

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