MOLECULAR ENVIRONMENTS OF 51 PLANCK COLD CLUMPS IN THE ORION COMPLEX

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ABSTRACT

A mapping survey of 51 Planck cold clumps projected on the Orion complex was performed with \( J = 1-0 \) lines of \(^{12}\)CO and \(^{13}\)CO with the 13.7 m telescope at the Purple Mountain Observatory. The mean column densities of the Planck gas clumps range from 0.5 to 9.5 \times 10^{21} \text{ cm}^{-2}, \) with an average value of \( (2.9 \pm 1.9) \times 10^{21} \text{ cm}^{-2}. \) The mean excitation temperatures of these clumps range from 7.4 to 21.1 K, with an average value of 12.1 \pm 3.0 K and the average three-dimensional velocity dispersion \( \sigma_{3D} \) in these molecular clumps is 0.66 \pm 0.24 km s\(^{-1}\). Most of the clumps have \( \sigma_{\text{vir}} \) larger than or comparable to \( \sigma_{\text{thm}} \). The \(^{12}\)CO column density of the molecular clumps calculated from molecular lines correlates with the aperture flux at 857 GHz of the dust emission. By analyzing the distributions of the physical parameters, we suggest that turbulent flows can shape the clump structure and dominate their density distribution on large scales, but not function on small scales due to local fluctuations. Eighty-two dense cores are identified in the molecular clumps. The dense cores have an average radius and local thermal equilibrium (LTE) mass of 0.34 \pm 0.14 pc and \( 38^{12}\)O \( M_\odot \), respectively. The structures of low column density cores are more affected by turbulence, while the structures of high column density cores are more affected by other factors, especially by gravity. The correlation of velocity dispersion versus core size is very weak for the dense cores. The dense cores are found to be most likely gravitationally bounded rather than pressure confined. The relationship between \( M_{\text{cl}} \) and \( M_{\text{LTE}} \) can be well fitted with a power law. The core mass function here is much flatter than the stellar initial mass function. The lognormal behavior of the core mass distribution is most likely determined by internal turbulence.

Key words: ISM: clouds – ISM: molecules – ISM: structure – stars: formation

Online-only material: color figures, extended figures, machine-readable tables

1. INTRODUCTION

The Orion complex is the best laboratory for studying star formation. Thousands of low-mass stars as well as a number of high-mass stars formed in this region within the last few million years (Bally et al. 2005; Hillenbrand 1997). Massive stars interact with molecular clouds in this region through powerful ionizing radiation, strong stellar wind, and supernova explosions (Cowie et al. 1979; Bally et al. 1987), and reshape and compress clouds into filamentary structures that contain three \( 10^5 M_\odot \) giant molecular clouds (GMCs; Orion A, Orion B, and Mon R2; Bally et al. 2005; Wilson et al. 2005). Triggered star formation has been suggested to explain the large spatial scale age gradients of distinguished star clusters in this region (Elmegreen & Lada 1977). Thus, it is important to study the properties of molecular clouds and star-forming activities in this region. In previous works, molecular clouds in this region have been widely studied through mapping surveys in transitions of CO and its isotopes (Maddalena et al. 1986; Bally et al. 1987; Castets et al. 1990; Kramer et al. 1996; Sakamoto et al. 1994; Nagahama et al. 1998; Wilson et al. 2001, 2005; Shimajiri et al. 2011). However, most of these studies focus on particular regions with active star formation (e.g., Orion A and Orion B) or poor spatial resolution, and seldom pay attention to the clouds comprising pre-stellar cores. The study of pre-stellar cores can help us understand the formation and evolution of dense cores, as well as the cause of the initial mass function (IMF; Planck Collaboration et al. 2011a). Studies of pre-stellar cores in this region are urgently needed. Recently, millimeter/submillimeter continuum surveys have revealed some quiescent cores in Orion (Li et al. 2007; Sadavoy et al. 2010), and the core mass function (CMF) for these quiescent cores has a power index of \( \sim \) -0.85 (Li et al. 2007). But continuum observations cannot provide us the velocity information of these cores and limit our understanding of core properties, such as velocity dispersions, core stabilities, and so on.

Investigations into density and temperature distributions, and the pressure supports in the pre-stellar cores are critically needed. Unfortunately, the properties of pre-stellar cores are not well known due to a lack of samples before the Planck satellite. Working at submillimeter/millimeter bands, the Planck satellite is unique and well suited for systemic surveys of cold clumps and has already provided a preliminary catalog of 10,783 cold clumps (the cold core Catalog of Planck Objects, C3PO; Planck Collaboration et al. 2011a). The Planck cold clumps in the C3PO sample were found with low column densities \( N_{\text{H}_2} \sim 0.1 \times 10^{22} \text{ cm}^{-2} \) and dust temperatures between 10 and 15 K (Planck Collaboration et al. 2011a). However, the physical properties of those cold clumps are still poorly known, especially their molecular environments. Recently, a single-point survey of 674 Planck cold clumps of the Early Cold Clump (ECC) catalog in the \( J = 1-0 \) transitions of \(^{12}\)CO, \(^{13}\)CO, and \(^{18}\)O was carried out using the 13.7 m telescope at the Purple Mountain Observatory (PMO; Wu et al. 2012). However, mapping observations are needed to study the structures and properties of these clumps in detail.

In this paper, we report on the results of a mapping survey of \(^{12}\)CO \((1-0)\) and its isotopes in 51 Planck cold clumps selected from the survey of Wu et al. (2012). The selected cold clumps are associated with the Orion GMC (Dame et al. 1987), and their coordinates and systemic velocities are listed in Table 1. The clumps have two velocity components and are distinguished with “a” and “b” at the end of the core names. The ninth column of Table 1 presents the aperture flux density at 857 GHz (apflux857) observed by the Planck satellite (Planck Collaboration et al. 2011b). The last column presents...
the associations of these cold clumps identified with SIMBAD. It can be seen that most of those cold clumps are associated with dark clouds or very weak IRAS point sources (a flux at 100 \(\mu\text{m}\) ranging from 2.3 to 35 Jy), indicating that they have low column densities and less star-forming activities. In this paper, the distances of these cold clumps are assumed to be 450 pc except for G180.81−19.66 and G185.80−09.12, which are associated with the \(\lambda\) Orion region and have distances of 400 pc (Planck Collaboration et al. 2011b).

Observations are introduced in the next section. The basic analysis and results of the molecular line observations are presented in the third section. We discuss the properties of the molecular environments of these cold clumps in Section 4. Section 5 summarizes this paper.

### 2. OBSERVATIONS

### 2.1. Observations of the Cold Clumps in the Orion GMC

There are 82 cold clumps in the ECC catalog projected in the Orion complex (Wu et al. 2012). We showed the distributions of the aperture flux density at 857 GHz (apflux857) for the mapped cold cores and for all the Planck cold clumps projected in the Orion complex. As shown in the right panel of Figure 1, the locations of the Planck cold clumps in the mapping survey are plotted as green “crosses.” The background image represents the \(H_\alpha\) emission (Finkbeiner 2003). The red and blue contours represent \(CO\) (1−0) (Dame et al. 2001) and IRAS 100 \(\mu\text{m}\) emission, respectively. CO emission roughly coincides with the IRAS 100 \(\mu\text{m}\) emission in space, but is not associated with \(H_\alpha\) emission. Nearly all the cold clumps are associated with CO emission and are distributed at the boundary or far from \(H_\alpha\) emission. The cold clumps form two large loops as denoted by the two dashed ellipses.

### 3. RESULTS

#### 3.1. Distribution of the Cold Clumps in the Orion GMC

There are 82 cold clumps in the ECC catalog projected in the Orion complex (Wu et al. 2012). We showed the distributions of the aperture flux density at 857 GHz (apflux857) for the mapped cold cores and for all the Planck cold clumps projected in the Orion complex. As shown in the right panel of Figure 1, the locations of the Planck cold clumps in the mapping survey are plotted as green “crosses.” The background image represents the \(H_\alpha\) emission (Finkbeiner 2003). The red and blue contours represent \(CO\) (1−0) (Dame et al. 2001) and IRAS 100 \(\mu\text{m}\) emission, respectively. CO emission roughly coincides with the IRAS 100 \(\mu\text{m}\) emission in space, but is not associated with \(H_\alpha\) emission. Nearly all the cold clumps are associated with CO emission and are distributed at the boundary or far from \(H_\alpha\) emission. The cold clumps form two large loops as denoted by the two dashed ellipses.

### 3.2. Overall Pictures of Molecular Clumps

#### 3.2.1. LTE Analysis

With the theory of radiation transfer and molecular excitation (Winnewisser et al. 1979; Garden et al. 1991), the analysis of the parameters of each clump was performed under the assumption of local thermal equilibrium (LTE). Assuming \(^{12}\text{CO}\) (1−0)
emission to be optically thick and the beam-filling factor to be a unit, the excitation temperature $T_{\text{ex}}$ can be directly calculated. The column densities of $^{13}$CO (1–0) were then calculated using the first equation in Garden et al. (1991). The column densities of H$_2$ were obtained by adopting typical abundance ratios of [H$_2$]/[12CO] = 10$^4$ and [13CO]/[12CO] = 60 in the interstellar medium.

In Figure 2, the excitation temperatures are presented in color scale and the column densities of H$_2$ are shown with contours. One can see that most of the clumps are very diffuse and temperature gradients are seen in many of them. The mean values of the column density and excitation temperature of each clump were obtained by analyzing the pixels within 30% of the contours in the column density maps and are presented in Columns 2 and 5 of Table 2. The mean column densities of these clumps range from 0.5 to 9.5 $\times$ 10$^{21}$ cm$^{-2}$, with an average value of (2.9 ± 1.9) $\times$ 10$^{21}$ cm$^{-2}$. The mean excitation temperatures of these clumps range from 7.4 to 21.1 K, with an average value of 12.1 ± 3.0 K. The column densities revealed by dust emission were found to range from 0.1 to 1.6 $\times$ 10$^{22}$ cm$^{-2}$ and dust temperatures ranged from 10 to 15 K in the C3PO samples (Planck Collaboration et al. 2011a), which are consistent with the excitations and column densities obtained here from CO emission. In the cores associated with red and weak IRAS sources, Wang et al. (2009) found an average excitation temperature of 9.7 K and an average H$_2$ column density of 8.9 $\times$ 10$^{21}$ cm$^{-2}$. The infrared dark clumps (IRDCs) were found to have a typical excitation temperature of 10 K and a typical column density of several $\times$ 10$^{22}$ cm$^{-2}$ (Du & Yang 2008). Compared with the IRAS sources and IRDCs, the Planck cold clumps have slightly larger excitation temperatures but much smaller column densities, indicating that these Planck cold clumps represent an earlier evolutionary phase in star formation.

3.2.2. First Moment Maps

The intensity-weighted velocity maps (first moment maps) of the clumps are shown in Figure 3 in color overlaid with the contours of the column densities of H$_2$. Velocity gradients are found in nearly all the clumps. Taking G185.80–09.12, for example, two compact cores are revealed in the map. The northern one has an average velocity of $-2.3 \pm 0.1$ km s$^{-1}$, while the central one has an average velocity of $-2.8 \pm 0.1$ km s$^{-1}$.

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3.2.3. Velocity Dispersion

The maps of the one-dimensional velocity dispersion of $^{13}$CO (1–0) are shown in Figure 4 in color overlaid with the contours of the column densities of H$_2$. One can see that the velocity dispersion is usually larger in the dense regions than in the less dense regions. The non-thermal ($\sigma_{\text{NT}}$) and thermal ($\sigma_{\text{Therm}}$) one-dimensional velocity dispersions in each clump are calculated as follows:

$$\sigma_{\text{NT}} = \left[ \frac{k T_{\text{ex}}}{m_{^{13}\text{CO}}} \right]^{1/2}$$

$$\sigma_{\text{Therm}} = \frac{k T_{\text{ex}}}{m_{H}\mu_{^{13}\text{CO}}}$$

where $m_{^{13}\text{CO}}$ and $T_{\text{ex}}$ are the one-dimensional velocity dispersion of $^{13}$CO (1–0) and the excitation temperature of each pixel in each clump, respectively. $k$ is Boltzmann’s constant, $m_{^{13}\text{CO}}$ is the mass of $^{13}$CO, $m_{H}$ is the mass of atomic hydrogen, and $\mu = 2.72$ is the mean molecular weight of the gas. Then the pixel value of three-dimensional velocity dispersion $\sigma_{3D}$ can be estimated as

$$\sigma_{3D} = \sqrt{3(\sigma_{\text{Therm}}^2 + \sigma_{\text{NT}}^2)}$$

The mean values of $\sigma_{\text{Therm}}$, $\sigma_{\text{NT}}$, and $\sigma_{3D}$ in each clump are presented in Table 2. The mean thermal one-dimensional velocity dispersion of these clumps ranges from 0.15 to 0.25 km s$^{-1}$, with an average value of 0.19 $\pm$ 0.02 km s$^{-1}$. The mean non-thermal one-dimensional velocity dispersion of these clumps ranges from 0.1 to 0.79 km s$^{-1}$, with an average value of 0.32 $\pm$ 0.16 km s$^{-1}$. The three-dimensional velocity dispersion $\sigma_{3D}$ ranges from 0.35 to 1.41 km s$^{-1}$, with an average value of 0.66 $\pm$ 0.24 km s$^{-1}$. There are 44 clumps with $\sigma_{\text{NT}}$ larger than $\sigma_{\text{Therm}}$. 

Figure 1. Left: distributions of the aperture flux density at 857 GHz (apflux857) for mapped sources and for all Planck cold clumps projected on the Orion complex. Right: distribution of Planck cold clumps in the Orion complex. Their locations are marked with green “crosses.” The background image represents the H$_2$ emission (Finkbeiner 2003). The red contours represent CO (1–0) emission (Dame et al. 2001). The contour levels are (0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9) $\times$ 10 K km s$^{-1}$. The blue contours show the IRAS 100 µm emission. The contour levels are (0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9) $\times$ 50 mJy sr$^{-1}$.

A color version of this figure is available in the online journal.
Figure 2. Contours represent the column density distribution. The contour levels are from 10% to 90% in steps of 10% of the peak value. The image in color shows the distribution of the excitation temperature in Kelvin. The cloud names are labeled in the upper-left corner of each panel.

(An extended, color version of this figure is available in the online journal.)
Table 2

Derived Parameters of Gas Emission over All of the Clouds

| Name             | $N_{\text{H}_2}$ (10$^{21}$ cm$^{-2}$) | $P$-value | $T_{\text{ex}}$ (K) | $P$-value | $\sigma_{\text{Therm}}$ (km s$^{-1}$) | $P$-value | $\sigma_{NT}$ (km s$^{-1}$) | $P$-value | $\sigma_{3D}$ (km s$^{-1}$) | $P$-value |
|------------------|---------------------------------------|-----------|---------------------|-----------|--------------------------------------|-----------|------------------------------|-----------|-------------------------------|-----------|
| G180.81−19.66    | 2.10$^{+0.39}_{-0.32}$               | 0.16      | 0.00               | 12.23$^{+0.53}_{-0.55}$ | 0.77       | 0.76                           | 0.19$^{+0.00}_{-0.00}$ | 0.79       | 0.76                           | 0.19$^{+0.02}_{-0.00}$ | 0.00     |
| G185.80−09.12    | 2.11$^{+0.66}_{-0.79}$               | 0.51      | 0.28               | 12.67$^{+0.93}_{-1.06}$ | 0.09       | 0.33                           | 0.20$^{+0.00}_{-0.00}$ | 0.18       | 0.33                           | 0.22$^{+0.07}_{-0.05}$ | 0.47     | 0.01                           | 0.52$^{+0.09}_{-0.08}$ | 0.07     | 0.31                           |
| G190.08−13.51    | 2.45$^{+0.64}_{-0.64}$               | 0.00      | 0.10               | 11.80$^{+0.44}_{-0.54}$ | 0.00       | 0.01                           | 0.19$^{+0.00}_{-0.00}$ | 0.00       | 0.01                           | 0.30$^{+0.09}_{-0.00}$ | 0.03     | 0.00                           | 0.63$^{+0.12}_{-0.14}$ | 0.00     | 0.09                           |
| G190.15−14.34    | 2.85$^{+0.82}_{-0.79}$               | 0.15      | 0.01               | 14.34$^{+1.13}_{-1.09}$ | 0.20       | 0.07                           | 0.21$^{+0.01}_{-0.01}$ | 0.14       | 0.07                           | 0.29$^{+0.05}_{-0.00}$ | 0.16     | 0.01                           | 0.63$^{+0.10}_{-0.08}$ | 0.01     | 0.47                           |
| G191.03−16.74    | 2.25$^{+0.52}_{-0.57}$               | 0.12      | 0.00               | 13.74$^{+0.92}_{-1.11}$ | 0.36       | 0.04                           | 0.20$^{+0.01}_{-0.01}$ | 0.13       | 0.04                           | 0.21$^{+0.04}_{-0.00}$ | 0.01     | 0.00                           | 0.52$^{+0.05}_{-0.05}$ | 0.56     | 0.12                           |
| G192.12−10.90    | 4.14$^{+1.13}_{-1.23}$               | 0.02      | 0.02               | 17.23$^{+2.23}_{-1.38}$ | 0.04       | 0.29                           | 0.23$^{+0.01}_{-0.01}$ | 0.11       | 0.28                           | 0.28$^{+0.05}_{-0.00}$ | 0.00     | 0.11                           | 0.62$^{+0.08}_{-0.08}$ | 0.00     | 0.01                           |
| G192.28−11.33    | 5.60$^{+1.13}_{-1.41}$               | 0.06      | 0.00               | 18.90$^{+1.37}_{-2.04}$ | 0.02       | 0.01                           | 0.24$^{+0.01}_{-0.01}$ | 0.02       | 0.01                           | 0.35$^{+0.06}_{-0.00}$ | 0.05     | 0.00                           | 0.74$^{+0.08}_{-0.07}$ | 0.04     | 0.00                           |
| G192.54−11.56    | 5.33$^{+0.58}_{-1.34}$               | 0.00      | 0.01               | 21.12$^{+0.79}_{-2.25}$ | 0.00       | 0.00                           | 0.25$^{+0.01}_{-0.01}$ | 0.00       | 0.00                           | 0.28$^{+0.03}_{-0.00}$ | 0.59     | 0.10                           | 0.65$^{+0.04}_{-0.04}$ | 0.73     | 0.79                           |
| G194.69−16.84    | 1.87$^{+0.58}_{-0.65}$               | 0.27      | 0.12               | 10.98$^{+0.73}_{-0.73}$ | 0.52       | 0.27                           | 0.18$^{+0.01}_{-0.01}$ | 0.39       | 0.27                           | 0.21$^{+0.04}_{-0.00}$ | 0.07     | 0.00                           | 0.49$^{+0.06}_{-0.07}$ | 0.36     | 0.10                           |
| G194.94−16.74    | 3.75$^{+0.84}_{-1.05}$               | 0.02      | 0.15               | 15.07$^{+0.95}_{-0.91}$ | 0.16       | 0.02                           | 0.21$^{+0.01}_{-0.01}$ | 0.06       | 0.02                           | 0.33$^{+0.05}_{-0.00}$ | 0.34     | 0.00                           | 0.66$^{+0.07}_{-0.08}$ | 0.87     | 0.29                           |
| G195.09−16.41    | 5.47$^{+1.91}_{-1.56}$               | 0.05      | 0.00               | 15.85$^{+0.76}_{-0.95}$ | 0.14       | 0.14                           | 0.22$^{+0.01}_{-0.01}$ | 0.26       | 0.14                           | 0.47$^{+0.08}_{-0.00}$ | 0.05     | 0.00                           | 0.91$^{+0.12}_{-0.15}$ | 0.02     | 0.25                           |
| G195.00−16.95    | 3.09$^{+0.66}_{-0.71}$               | 0.10      | 0.02               | 14.21$^{+0.71}_{-0.66}$ | 0.56       | 0.36                           | 0.21$^{+0.01}_{-0.00}$ | 0.52       | 0.35                           | 0.29$^{+0.06}_{-0.00}$ | 0.21     | 0.00                           | 0.64$^{+0.08}_{-0.07}$ | 0.11     | 0.04                           |
| G196.21−15.50    | 2.22$^{+0.74}_{-0.79}$               | 0.41      | 0.03               | 14.38$^{+0.75}_{-0.74}$ | 0.74       | 0.44                           | 0.21$^{+0.01}_{-0.01}$ | 0.59       | 0.44                           | 0.27$^{+0.09}_{-0.00}$ | 0.74     | 0.06                           | 0.62$^{+0.13}_{-0.13}$ | 0.20     | 0.45                           |
| G198.03−15.24    | 2.26$^{+0.68}_{-0.65}$               | 0.31      | 0.01               | 14.06$^{+0.80}_{-0.73}$ | 0.48       | 0.15                           | 0.21$^{+0.01}_{-0.01}$ | 0.32       | 0.16                           | 0.22$^{+0.05}_{-0.00}$ | 0.69     | 0.01                           | 0.52$^{+0.06}_{-0.07}$ | 0.44     | 0.38                           |

Note. The errors throughout all the tables are calculated from the first and third quartiles.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
Figure 3. Contours represent the column density distribution. The contour levels are from 10% to 90% in steps of 10% of the peak value. The first momentum maps of $^{13}$CO (1–0) emission are shown in color in km s$^{-1}$. The cloud names are labeled in the upper-left corner of each panel.

(An extended, color version of this figure is available in the online journal.)
Figure 4. Contours represent the column density distribution. The contour levels are from 10% to 90% in steps of 10% of the peak value. The second momentum (velocity dispersion) maps of $^{13}$CO (1–0) emission are shown in color in km s$^{-1}$. The cloud names are labeled in the upper-left corner of each panel.

(An extended, color version of this figure is available in the online journal.)
and in the remaining clumps \( \sigma_{\text{NT}} \) and \( \sigma_{\text{Therm}} \) are comparable. The mean ratio of \( \sigma_{\text{NT}} \) to \( \sigma_{\text{Therm}} \) in these clumps is 1.65 \pm 0.76.

Star-forming activities such as infall, outflow, and rotation could increase the non-thermal velocity dispersion. However, no significant star-forming activities were found in those cold and low density Planck clumps. These clumps are more quiescent than the other typical star-forming regions. Thus, the non-thermal motions in the Planck cold clumps are mainly determined by turbulence and the non-thermal velocity dispersion can be used as a measurement of the turbulent strength.

3.3. The Properties of Dense Cores

In spite of the diffuse aspects, dense parts also exist in the clumps. The individual dense cores are identified within 50% of the contours of the column density distribution. Thirteen clumps are too diffuse to identify a dense core and 15 clumps contain only one dense core. In the other clumps, more than one dense core is identified. In total, 82 dense cores are identified. The dense cores are fitted with a two-dimensional Gaussian function. The positions of each dense core are shown in Column 2 of Table 3. The radii of the cores are defined as \( R = \sqrt{(a-b)/2} \), where \( a \) and \( b \) are the sizes of the minor and major axes, respectively. The systemic velocities of each dense core are obtained by averaging the pixel values within their radii in the first moment images. The deconvolved sizes, radii, and systemic velocities are shown in Columns 2–4 in Table 4, respectively. The radii of the cores range from 0.07 to 0.55 pc, with an average value of 0.27 \pm 0.12 pc. The statistical results for column densities of \( \text{H}_2 \), excitation temperatures, and velocity dispersions within the radii of cores are summarized in Table 3. The average column density of \( \text{H}_2 \) and the excitation temperature of the dense cores are (3.3 \pm 2.1) \times 10^{21} \text{ cm}^{-2} \) and 12.5 \pm 3.5 K, respectively, which are slightly larger than the average values for all clumps. The average values of \( \sigma_{\text{Therm}} \), \( \sigma_{\text{NT}} \), and \( \sigma_{3D} \) are 0.19 \pm 0.03, 0.33 \pm 0.14, and 0.67 \pm 0.22 \text{ km s}^{-1} \), respectively, which are the same as the average values for all the clumps.

The volume densities of each core are inferred as \( n = N_{\text{H}_2}^{\text{Peak}} / 2R \), where \( N_{\text{H}_2}^{\text{Peak}} \) is the peak \( \text{H}_2 \) column density. The volume densities range from 0.9 to 5.6 \times 10^3 \text{ cm}^{-3} \), with an average value of (2.4 \pm 1.1) \times 10^3 \text{ cm}^{-3} \). The LTE masses of the cores are estimated as \( M_{\text{LTE}} = (4/3)\pi R^3 \cdot n \cdot m_{\text{H}_2} \cdot \mu_e \), where \( m_{\text{H}_2} \) is the mass of a hydrogen molecule and \( \mu_e \) is the mean atomic weight of the gas. The LTE masses range from 0.3 to 270 \( M_\odot \), with an average value of 38_{-30}^{+55} M_\odot.

4. DISCUSSION

4.1. The Probability Distributions of the Derived Parameters in the GMC Scale

The lognormal behaviors of volume or column density in molecular clouds have been frequently reported in recent observations (Ridge et al. 2006; Froebrich et al. 2007; Goodman et al. 2009), and are often interpreted as a consequence of supersonic turbulence in observed clouds (Vázquez-Semadeni 1994). However, clouds that have already formed stars also exhibit power-law-like tails at large column densities besides the lognormal-like shape at low column densities (Kainulainen et al. 2009; Froebrich & Rowles 2010). In simulations, the power-law-like tails are often attributed to the formation of local collapsing sites in turbulent flows (Kritsuk et al. 2011; Ballesteros-Paredes et al. 2011). The development of power-law tails at high densities is thus a consequence of the transition from more diffuse, turbulence-dominated clouds to denser, star-forming, collapsing clouds (Ballesteros-Paredes et al. 2011). Thus, the distributions of volume or column densities in clumps can be used as an indicator of their evolutionary states. Additionally, investigating the distributions of the other parameters, such as velocity dispersion and excitation temperature, can help us understand the formation of the column or volume density distributions. For example, if non-thermal velocity dispersion rather than thermal velocity dispersion (or excitation temperature) has a similar distribution as the column density, we can argue that the non-thermal motions (turbulence) play a more important role in the formation of density distribution as well as the cloud structure.

We investigate the probability distributions of the derived parameters on the GMC scale. The mean parameters used to generate the cumulative distributions in Figure 5 are derived by averaging all the pixel values within 30% of the contours of the column density image in each clump. The Kolmogorov–Smirnov (K-S) test is applied to check whether the distributions of the parameters follow a normal or lognormal distribution. The motivation for modeling the distributions with a normal shape is to test whether the variables are randomly changed. Moreover, a variable having a lognormal distribution can be thought of as the multiplicative product of many independent random variables. Thus it is worth modeling the distributions of the parameters with a normal distribution for comparison. The null hypothesis is that the distribution of the derived parameter can be described with a normal or lognormal distribution. The decision to reject or accept the null hypothesis is based on comparing the P-value with the desired significance level, which is 0.05 in this paper. Thus, if the P-values from the K-S test are larger than 0.05, the derived parameter should follow the reference distribution.

As shown in Figure 5, the distributions of the derived parameters (\( N_{\text{H}_2} \), apflux857, \( T_{\text{ex}} \), \( \sigma_{\text{Therm}} \), \( \sigma_{\text{NT}} \), \( \sigma_{3D} \)) for the whole region, including all the mapped clumps, can all be fitted with a lognormal distribution. Besides \( \sigma_{\text{Therm}} \), the other five parameters also follow a normal distribution. However, the P-values of the K-S test for a normal distribution hypothesis are much smaller than that for a lognormal distribution hypothesis, indicating that the underlying distributions of these parameters are more likely to have a lognormal shape. The P-values for the lognormal distribution hypothesis of \( N_{\text{H}_2} \) and apflux857 are as high as \( \sim 0.9 \), indicating perfect lognormal distributions. In previous works, the lognormal behavior of the column density distribution in clumps without star formation was interpreted as having been determined by turbulent motions. We also noticed that the P-value for the lognormal distribution hypothesis of \( \sigma_{\text{NT}} \) is much larger than that of \( \sigma_{\text{Therm}} \), suggesting that turbulence dominates the density distribution in a sense.

We also investigate the parameter distributions of the dense cores in this region on the GMC scale. As shown in Figure 6, the distributions of the derived parameters (\( N_{\text{H}_2} \), \( n \), \( T_{\text{ex}} \), \( \sigma_{\text{Therm}} \), \( \sigma_{\text{NT}} \), \( \sigma_{3D} \)) of the cold cores are also fitted with normal and lognormal distributions. Besides \( \sigma_{\text{Therm}} \), the distributions of the other five parameters can be well described by a lognormal distribution with P-values larger than 0.3. The volume density \( n \), \( \sigma_{\text{NT}} \), and \( \sigma_{3D} \) can also be fitted with a normal distribution with much lower P-values, indicating that their distributions prefer a lognormal shape rather than a normal shape. The volume density has a remarkable lognormal distribution with a P-value as large as 0.83. The column densities of these dense cores can also be fitted with a lognormal distribution (see panel (a) of Figure 6), but the P-value (0.44) is much lower than that of all
### Table 3
Derived Parameters of the Dense Cores

| Name       | Offset            | $N_{H_2}$ Max | Mean | $P$-value | $T_{ex}$ Mean | $P$-value | $\sigma_{Thm}$ Mean | $P$-value | $\sigma_{NT}$ Mean | $P$-value | $\sigma_{3D}$ Mean | $P$-value |
|------------|-------------------|---------------|------|-----------|---------------|-----------|----------------------|-----------|---------------------|-----------|---------------------|-----------|
|            |                   | ($^{10^{21}}$ cm$^{-2}$) |      |           | ($K$)         |           |                      |           |                     |           |                      |           |
| G185.80−09.12 | $(-69, -19)$       | 4.37          | 2.95$^{+0.72}_{-0.31}$ | 0.47 | 0.02      | 13.10$^{+0.91}_{-0.92}$ | 0.21   | 0.32                  |           | 0.28$^{+0.05}_{-0.04}$ | 0.22   | 0.03                 | 0.60$^{+0.06}_{-0.05}$ | 0.30 | 0.11|
|            | $(-134,290)$      | 3.36          | 2.25$^{+0.62}_{-0.61}$ | 0.90 | 0.00      | 11.89$^{+0.51}_{-0.35}$ | 0.48   | 0.42                  |           | 0.19$^{+0.00}_{-0.00}$ | 0.45   | 0.42                 | 0.23$^{+0.06}_{-0.04}$ | 0.86 | 0.61|
| G190.08−13.51 | (110,106)         | 4.86          | 3.11$^{+0.64}_{-0.67}$ | 0.12 | 0.00      | 11.91$^{+0.20}_{-0.40}$ | 0.19   | 0.00                  |           | 0.36$^{+0.06}_{-0.07}$ | 0.27   | 0.33                 | 0.39$^{+0.05}_{-0.04}$ | 0.29 | 0.02|
|            | (25,−62)          | 4.86          | 3.49$^{+0.28}_{-0.40}$ | 0.72 | 0.25      | 11.69$^{+0.20}_{-0.21}$ | 0.19   | 0.68                  |           | 0.75$^{+0.08}_{-0.06}$ | 0.00   | 0.06                 | 0.82$^{+0.05}_{-0.09}$ | 0.98 | 0.98|
|            | (17,−89)          | 4.86          | 4.03$^{+0.26}_{-0.46}$ | 0.99 | 0.89      | 11.66$^{+0.14}_{-0.18}$ | 0.96   | 0.96                  |           | 0.35$^{+0.08}_{-0.09}$ | 0.18   | 0.12                 | 0.44$^{+0.03}_{-0.04}$ | 0.97 | 0.98|
|            | (22,62)           | 4.86          | 3.04$^{+0.60}_{-0.60}$ | 0.14 | 0.00      | 11.59$^{+0.38}_{-0.31}$ | 0.25   | 0.12                  |           | 0.31$^{+0.04}_{-0.04}$ | 0.43   | 0.50                 | 0.31$^{+0.04}_{-0.04}$ | 0.97 | 1.00|
| G190.15−14.34 | (122,−27)         | 5.27          | 3.32$^{+0.66}_{-0.48}$ | 0.74 | 0.05      | 15.03$^{+0.85}_{-0.83}$ | 0.37   | 0.50                  |           | 0.66$^{+0.06}_{-0.06}$ | 0.00   | 0.00                 | 0.69$^{+0.12}_{-0.13}$ | 0.74 | 0.03|
|            | (−18,−31)         | 5.29          | 3.36$^{+0.71}_{-0.66}$ | 0.88 | 0.09      | 14.93$^{+0.96}_{-0.87}$ | 0.67   | 0.45                  |           | 0.68$^{+0.10}_{-0.08}$ | 0.51   | 0.27                 | 0.68$^{+0.10}_{-0.08}$ | 0.45 | 0.27|
|            | (−340,−5)         | 5.29          | 4.03$^{+0.53}_{-0.42}$ | 0.84 | 0.65      | 15.04$^{+0.80}_{-0.73}$ | 0.29   | 0.25                  |           | 0.42$^{+0.07}_{-0.05}$ | 0.27   | 0.25                 | 0.82$^{+0.10}_{-0.08}$ | 0.32 | 0.26|
| G191.03−16.74 | (−81,72)          | 3.69          | 2.40$^{+0.42}_{-0.44}$ | 0.55 | 0.07      | 13.44$^{+0.92}_{-1.09}$ | 0.00   | 0.00                  |           | 0.23$^{+0.03}_{-0.02}$ | 0.11   | 0.02                 | 0.53$^{+0.04}_{-0.04}$ | 0.56 | 0.23|
|            | (74,−80)          | 3.69          | 2.44$^{+0.28}_{-0.28}$ | 0.04 | 0.00      | 13.25$^{+0.94}_{-0.94}$ | 0.05   | 0.07                  |           | 0.23$^{+0.03}_{-0.02}$ | 0.06   | 0.07                 | 0.35$^{+0.04}_{-0.04}$ | 0.25 | 0.06|
| G192.12−10.90 | (−39,−33)         | 7.33          | 4.36$^{+0.74}_{-0.71}$ | 0.92 | 0.68      | 17.04$^{+0.73}_{-0.73}$ | 0.82   | 0.65                  |           | 0.28$^{+0.02}_{-0.02}$ | 0.02   | 0.00                 | 0.63$^{+0.03}_{-0.03}$ | 0.01 | 0.02|
|            | (−212,−113)       | 7.33          | 5.09$^{+1.12}_{-1.00}$ | 0.75 | 0.09      | 17.99$^{+0.85}_{-0.55}$ | 0.34   | 0.19                  |           | 0.33$^{+0.05}_{-0.05}$ | 0.29   | 0.09                 | 0.70$^{+0.07}_{-0.08}$ | 0.38 | 0.13|
|            | (−326,−338)       | 7.81          | 5.65$^{+0.64}_{-0.54}$ | 0.75 | 0.31      | 19.61$^{+1.47}_{-1.64}$ | 0.48   | 0.39                  |           | 0.34$^{+0.02}_{-0.02}$ | 0.43   | 0.52                 | 0.72$^{+0.03}_{-0.04}$ | 0.36 | 0.42|
| G192.28−11.33 | (240,−235)        | 9.60          | 6.37$^{+1.66}_{-1.21}$ | 0.08 | 0.01      | 20.11$^{+1.49}_{-1.47}$ | 0.24   | 0.47                  |           | 0.34$^{+0.07}_{-0.07}$ | 0.09   | 0.02                 | 0.74$^{+0.10}_{-0.10}$ | 0.14 | 0.07|
|            | (−164,−264)       | 9.96          | 6.48$^{+1.32}_{-1.02}$ | 0.22 | 0.00      | 21.15$^{+1.91}_{-1.83}$ | 0.25   | 0.12                  |           | 0.33$^{+0.03}_{-0.02}$ | 0.46   | 0.12                 | 0.72$^{+0.05}_{-0.04}$ | 0.62 | 0.39|
|            | (−7,−105)         | 10.04         | 7.21$^{+0.94}_{-0.83}$ | 0.28 | 0.00      | 19.38$^{+2.47}_{-2.48}$ | 0.01   | 0.08                  |           | 0.40$^{+0.04}_{-0.04}$ | 0.49   | 0.04                 | 0.81$^{+0.06}_{-0.05}$ | 0.45 | 0.08|

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
Figure 5. Cumulative distributions of the derived parameters averaged over all of the clouds. The names of the parameters are labeled on the top of each panel. The blue curve is the data distribution. The red solid and green dashed lines represent the best normal and lognormal distribution fits, respectively.

(A color version of this figure is available in the online journal.)
Figure 6. Cumulative distributions of the derived parameters averaged over the dense cores. The names of the parameters are labeled on the top of each panel. The blue curve is the data distribution. The red solid and green dashed lines represent the best normal and lognormal distribution fits, respectively.

(A color version of this figure is available in the online journal.)
of the clumps (0.88) (see panel (a) of Figure 5). The significant variance reflects that the dense cores are more evolved regions in the clumps, which begin to decouple from the general turbulent field and are more affected by gravity. The $\sigma_{\text{NT}}$ distribution has a lognormal behavior with a larger $P$-value of 0.89 than that of $\sigma_{\text{Therm}}$ (0.03), indicating that turbulent motions dominate the shaping of the clump structures and induce density fluctuations on the GMC scale.

4.2. The Probability Distributions of Derived Parameters in the Clump Scale

The distributions of the parameters in each clump were studied separately. For each clump, the distributions of the pixel values of the derived parameters ($N_{\text{H}_2}, T_{\text{ex}}, \sigma_{\text{Therm}}, \sigma_{\text{NT}}, \sigma_{3D}$) were investigated. The distributions were tested for normal and lognormal distribution hypotheses with the K-S test. The $P$-values from the K-S test are summarized in Table 2. The cumulative distributions of the $P$-values for a normal and a lognormal distribution hypothesis are shown in panels (a) and (b) of Figure 7, respectively. One can see that the distributions of the five parameters in more than half of the clumps are more likely to be fitted with a normal distribution with a $P$-value larger than 0.05. Thirty-one $P$-values for a normal distribution have $P$-values larger than 0.05. In panel (b), we can also see in a large number of the clumps that the five parameters are lognormally distributed.

We also investigate the distributions of the pixel values of the derived parameters ($N_{\text{H}_2}, T_{\text{ex}}, \sigma_{\text{Therm}}, \sigma_{\text{NT}}, \sigma_{3D}$) in each dense core. The distributions are also tested for a normal and lognormal distribution hypothesis with the K-S test, and the $P$-values from the K-S test are summarized in Table 3. The cumulative distributions of the $P$-values for a normal and a lognormal distribution hypothesis are shown in panels (a) and (b) of Figure 7, respectively. In panel (a), the cumulative density distributions have an almost linear shape. More than 90% of the dense cores show cumulative density distributions have an almost linear shape. Except for $\sigma_{3D}$, the other four parameters in these clumps are more likely to be fitted with a normal distribution rather than a lognormal distribution. Those parameters seem to prefer a normal distribution on small scales but favor a lognormal distribution on a large scale (see Section 4.1). It seems that the local values of these parameters ($N_{\text{H}_2}, T_{\text{ex}}, \sigma_{\text{Therm}}, \sigma_{\text{NT}}$) are essentially random, leading to a normal distribution. If the fluctuations of the parameters on small scales are independent of one another, the distributions of the average parameters of each clump are thus lognormally distributed (Vázquez-Semadeni 1994). In panel (d) of Figure 7, the bin-averaged $P$-values versus the bin-averaged column densities are plotted. The width of the bins is varied to guarantee that the number of clumps in each bin are similar. Except for $\sigma_{3D}$, the bin-averaged $P$-values for a normal hypothesis are larger than that for a lognormal hypothesis in each $N_{\text{H}_2}$ bin, which is revealed by the fact that the solid lines in panel (d) are always above the dashed lines. We also noticed that the bin-averaged $P$-values of $N_{\text{H}_2}, T_{\text{ex}}, \sigma_{\text{Therm}},$ and $\sigma_{\text{NT}}$ for a normal distribution hypothesis decrease roughly with the column density.

![Table 4: Derived Parameters of the Dense Cores](images/table4.png)

(The table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
Figure 7. Statistics of the K-S test P-values for parameter distributions in each clump (cloud). (a) The P-value distribution from the K-S test for a normal distribution hypothesis. (b) The P-value distribution from the K-S test for a lognormal distribution hypothesis. (c) The distribution of the ratio $P(\text{lognormal}) / P(\text{normal})$. (d) Bin-averaged P-values vs. bin-averaged column densities. (A color version of this figure is available in the online journal.)

cores, the distributions of $T_{\text{ex}}$ and $\sigma_{\text{Therm}}$ are more likely to follow a normal behavior. In more than 75% of the dense cores, the $\sigma_{3D}$ favors a normal distribution rather than a lognormal distribution, that is $P(\text{lognormal}) / P(\text{normal}) < 1$. And in more than 90% of the dense cores, the $\sigma_{\text{NT}}$ and $N_{\text{H}_2}$ can be better fitted by a normal distribution rather than by a lognormal distribution. All of the above indicates that, on small scales, the local values of these parameters are more likely normally distributed. In panel (d), we also investigated the bin-averaged P-values versus the column density. It can be seen that all the solid lines (normal distribution) are located above the dashed lines (lognormal distribution), which also reveals that these parameters favor a normal distribution on small scales. All the P-values of these parameters seem to roughly decrease with column density, with the maximum value peaking at $(2 - 2.5) \times 10^{21} \text{ cm}^{-2}$. This evolutionary behavior reflects that the structures with low column density cores are more affected by turbulence, while the structures with high column density cores are more affected by other factors, especially by gravity.

4.3. Turbulence-dominated Clumps

As discussed in Sections 4.1 and 4.2, the distributions of the parameters, especially the density distribution, have lognormal behaviors on large scales (GMC) and normal behaviors on small scales (clump and dense cores), which indicates that these clumps are turbulence dominated. In other words, the clump structures are more likely shaped by turbulent flows (Vázquez-Semadeni 1994).

The left panel of Figure 9 shows the relationship between the $H_2$ column density and three-dimensional velocity dispersion averaged over all the clumps. It can be seen that the velocity dispersion increases with the $H_2$ column density. The relationship can be better described as a power law rather than a linear relation. The linear fitting is
\[ \sigma_{3D}/(\text{km s}^{-1}) = (0.11 \pm 0.01)(N_{\text{H}_2}/(10^{21} \text{ cm}^{-2})) + (0.36 \pm 0.04), \]

with \( R^2 = 0.64 \), while the power-law fitting is \( \sigma_{3D}/(\text{km s}^{-1}) = (0.41 \pm 0.02)(N_{\text{H}_2}/(10^{21} \text{ cm}^{-2})))^{0.47 \pm 0.04} \), with \( R^2 = 0.74 \).

We also noticed that the ratio of non-thermal to thermal velocity dispersion increases with the H\(_2\) column density. As shown in the right panel of Figure 9, the relationship can be better fitted with a power law rather than a linear relation. The linear fitting is \( \sigma_{\text{NT}}/\sigma_{\text{Therm}} = (0.25 \pm 0.05)(N_{\text{H}_2}/(10^{21} \text{ cm}^{-2})) + (0.93 \pm 0.15) \), with \( R^2 = 0.37 \), while the power-law fitting is \( \sigma_{\text{NT}}/\sigma_{\text{Therm}} = (0.98 \pm 0.07)(N_{\text{H}_2}/(10^{21} \text{ cm}^{-2}))))^{0.49 \pm 0.07} \), with \( R^2 = 0.49 \).

The ratio of non-thermal to thermal pressure in one clump can be estimated as \( R_p = \sigma_{\text{NT}}/\sigma_{\text{Therm}}^2 \). As discussed in Section 3.2.3, most of the clumps have \( \sigma_{\text{NT}} \) larger than or comparable to \( \sigma_{\text{Therm}} \). Thus, \( R_p \) is larger than the unit in most of the clumps, suggesting that the clumps associated with Planck cold clumps are mostly non-thermally dominated. Since the ratio of non-thermal to thermal velocity dispersion increases with the H\(_2\) column density, the non-thermal pressure becomes more dominant in dense clumps, i.e., the denser clumps are more turbulent. However, once gravity dominates pressure, the gas can collapse until the densest parts become optically thick. This allows the gas to heat up adiabatically and the gas pressure to increase dramatically while the supersonic turbulence may decay quickly on a dynamical timescale (Shu et al. 1987; Zinnecker & Yorke 2007). The low column densities and excitation temperatures as well as the large ratio of non-thermal to thermal pressure indicate that those clumps are still turbulence dominated and not greatly affected by gravity. In other words, most parts of these clumps are still quiescent and have not suffered gravitational contracting.

**4.4. Correlations between Dust and Gas Emission**

Dust and molecular gas are considered to coexist in molecular clumps. In the sub-millimeter band, dust emission is always
optically thin and can be treated as a good tracer of column density. In Figure 10, we plot the H$_2$ column densities of the clumps obtained from $^{13}$CO data as a function of the aperture flux at 857 GHz. The column density increases with the flux at 857 GHz. The linear fitting is $N_{H_2}/(10^{21}$ cm$^{-2}) = 0.01$(apflux857/(Jy)) + (1.29 ± 0.30), with $R^2 = 0.47$, while the power-law fitting has the form $N_{H_2}/(10^{21}$ cm$^{-2}) = (0.13 ± 0.06)$(apflux857/(Jy))$^{0.61±0.09}$, with $R^2 = 0.47$. As discussed in Section 4.1, the column density and the flux (at 857 GHz) of the clumps are both following a lognormal distribution with large $P$-values. All the above indicates that the dust and gas are well mixed in these clumps.

4.5. The Larson Relationship

The correlation of the velocity dispersion versus region size has a power-law form (Larson 1981). However, in several other surveys the Larson relationship was not valid or very weak (Buckle et al. 2009; Kramer et al. 1996; Onishi et al. 2002). The plot of the three-dimensional velocity dispersion against the radius of the dense cores is shown in Figure 11. The correlation can be represented as $\sigma_{3D}/$(km s$^{-1}$) = (0.92 ± 0.08)(R/(pc))$^{0.31±0.07}$, with $R^2 = 0.21$. The correlation is very weak, and the power index found here is also smaller than that in Larson (1981), which is 0.38. The weak correlation could be due to the small range in $R$ (0.08–0.65 pc) and $\sigma_{3D}$ (0.34–1.51 km s$^{-1}$), and the large scatter in the values. The uncertainties of the distance should also be a cause of the weak relationship. However, the Larson relationship may not be valid on small scales. As discussed in Sections 4.1 and 4.2, turbulence dominates the clump structure and density distribution on large scales but not on small scales. Small-scale structures are more easily affected by the fluctuations of density and temperature.
4.6. Gravitational Stabilities of the Dense Cores

Assuming that the dense cores are gravitationally bound isothermal spheres with a density profile of $\rho \propto R^n$, the virial mass $M_{\text{vir}}$ can be calculated following MacLaren et al. (1988) and Williams et al. (1994):

$$M_{\text{vir}} = \frac{5R\sigma_3D}{3\gamma G},$$

(4)

where $G$ is the gravitational constant. Assuming that the density profile is $\rho \propto R^{-2}$, $\gamma = 5/3$. The virial masses are listed in Column 7 of Table 4.

In molecular clumps, many factors, including thermal pressure, turbulence, and magnetic field, support the gas against gravity collapse. The Jeans mass, which takes into account thermal and turbulent support, can be expressed as (Hennebelle & Chabrier 2008)

$$M_J \approx 1.0a_J \left( \frac{T_{\text{eff}}}{10 K} \right)^{3/2} \left( \frac{\mu}{2.33} \right)^{-1/2} \left( \frac{n}{10^4 \text{ cm}^{-3}} \right)^{-1/2} M_\odot,$$

(5)

where $a_J$ is a dimensionless parameter of the order unity, which takes into account the geometrical factor, $\mu = 2.72$ is the mean molecular weight, $n$ is the volume density of H$_2$, and $T_{\text{eff}} = C_{s,\text{eff}} v_{\text{H}}^2/k$ is the effective kinetic temperature. The effective sound speed, $C_{s,\text{eff}}$ including turbulent support can be calculated as

$$C_{s,\text{eff}} = \left[ (\sigma_{\text{NT}})^2 + (\sigma_{\text{Therm}})^2 \right]^{1/2}.$$

(6)

The calculated Jeans masses are listed in the eighth column of Table 4.

About 64 (78%) dense cores have virial masses larger than LTE masses, and only 10 (12%) dense cores have virial masses larger than three times the LTE masses. The others (88%) have virial masses consistent with LTE masses within a factor of three. The average ratio of virial mass to LTE mass is 1.36. About 45% of the dense cores have Jeans masses larger than LTE masses. More than 84% of cores have Jeans masses consistent with an LTE mass within a factor of three. The average ratio of Jeans mass to LTE mass is 1.89. Eighty-three percent of dense cores have both virial and Jeans masses consistent with LTE masses within a factor of three. Considering the uncertainties in estimating the masses, it seems that most of the cores are gravitationally bounded, and the internal thermal and turbulent pressure can support them against gravitational collapse.

The left panel of Figure 12 shows the relationship between $M_{\text{vir}}$ and $M_{\text{LTE}}$. The relationship can be well fitted with a power law of $M_{\text{vir}}/(M_\odot) = (4.96 \pm 0.49)[M_{\text{LTE}}/(M_\odot)]^{0.61\pm0.03}$, with $R^2 = 0.83$. The power index obtained here is very close to the value obtained in Orion B (0.67) (Ikeda et al. 2009) and NGC 2071 (0.6) (Buckle et al. 2009). The pressure-confined cores were thought to have $M_{\text{vir}} \propto M_{\text{LTE}}^{1/3}$ (Bertoldi & McKee 1992). The power-law index for the pressure-confined cores is significantly smaller than that for the dense cores obtained here, indicating that the dense cores are most likely not pressure confined, but gravitationally bounded (Ikeda et al. 2009). In the right panel of Figure 12, we plot $M_J$ versus $M_{\text{LTE}}$, whose relationship can also be well fitted with a power law. The power law has a form of $M_J/(M_\odot) = (5.40 \pm 0.80)[M_{\text{LTE}}/(M_\odot)]^{0.43\pm0.05}$, with $R^2 = 0.51$.

As shown in the last column of Table 4, only 11 cores are found to be associated with IRAS point sources. However, these IRAS point sources are very weak with 100 $\mu$m flux ranging from 2 to 30 Jy. It seems that star-forming activities have not taken in these cores, and most of them may be starless.

4.7. Core Mass Function

The differential CMF is usually found to follow a power-law spectrum like $dN/dM \sim M^{-\alpha}$. However, the shape of the mass spectrum is far from fixed and a broken power-law appearance is also suggested in some surveys (Buckle et al. 2009). In the left panel of Figure 13, we plot the CMF of the dense cores. The CMF can be well fitted with a power law for $15 < M_{\text{LTE}}/M_\odot < 200$. The power law gives $\alpha = 1.32 \pm 0.08$. Compared with $\alpha$ (2.35) of the stellar IMF (Salpeter 1955), the power-law shape of the CMF here is much flatter. As shown in the right panel of Figure 13, the masses of the cores are also found to be lognormally distributed with a $P$-value from the K-S test as large as 0.87. The mean ($\mu$) and standard deviation ($\sigma$) of the lognormal distribution are 2.9 and 1.3, corresponding...
to a mass of 18 and 4 $M_\odot$, respectively. As discussed in Section 4.1, the non-thermal velocity distribution also prefers to follow a lognormal shape while the thermal dispersion does not, indicating non-thermal motions (turbulence) dominate the evolution of clumps. We argue that supersonic turbulence can create dense cores with a lognormal distribution of densities and masses in the clumps, which is consistent with the simulations (Veltchev et al. 2011).

5. SUMMARY

We performed a mapping survey of CO, $^{13}$CO and C$^{18}$O in molecular lines, $J = 1 - 0$, toward 51 Planck cold clumps projected on the Orion complex. The main findings in this work are as follows.

1. The mean column densities of the molecular clumps associated with the Planck cold clumps range from 0.5 to $9.5 \times 10^{21}$ cm$^{-2}$, with an average value of $(2.9 \pm 1.9) \times 10^{21}$ cm$^{-2}$. The mean excitation temperatures of these clumps range from 7.4 to 21.1 K, with an average value of $12.1 \pm 3.0$ K. The H$_2$ column densities and excitation temperatures obtained here are comparable to those values obtained from dust emission in the C3PO samples. However, Planck cold clumps have slightly larger excitation temperatures but much smaller column densities when compared to IRAS sources and IRDCs, indicating that these Planck cold clumps represent an earlier evolutionary phase of the dense cores. The power index of the relationship is found to be $\alpha = 0.65$ pc, with an average value of 0.24 $\pm$ 0.14 pc. Their LTE masses range from 0.3 to 270 $M_\odot$, with an average value of $38^{+5}_{-30} M_\odot$.

3. We found that $N_{\rm H_2}$, apflux857, $T_{\rm ex}$, $\sigma_{\rm Therm}$, $\sigma_{\rm NT}$, $\sigma_{\rm 3D}$, and volume density $n$ have a lognormal distribution on large scales (in the whole GMC), but $N_{\rm H_2}$, $T_{\rm ex}$, $\sigma_{\rm Therm}$, $\sigma_{\rm NT}$ more likely favor a normal distribution on small scales (in each clump). It seems turbulent flows can shape the clump structure and dominate their density distribution on large scales, but not function on small scales due to local fluctuations. In each clump or dense core, we also noticed that the distributions of $N_{\rm H_2}$, $T_{\rm ex}$, $\sigma_{\rm Therm}$, $\sigma_{\rm NT}$ deviate from normal or lognormal distributions at high column densities, indicating that the structures of low column density cores are more affected by turbulence, but the structures of high column density cores are more affected by other factors, especially by gravity.

4. The H$_2$ column density of molecular clumps, calculated from molecular lines, correlates with the aperture flux at 857 GHz of the dust emission.

5. The correlation of the velocity dispersion versus core size, i.e., the Larson relationship, is very weak for dense cores. The power index of the relationship is found to be $0.31 \pm 0.07$, smaller than the value obtained by Larson (1981). The Larson relationship seems not to be valid on small scales, which also indicates that turbulence dominates the clump structure and density distribution on large scales but not on small scales.

6. The dense cores are found to be mostly gravitationally bounded by analyzing their virial masses and Jeans masses. The relationship between $M_{\rm vir}$ and $M_{\rm LTE}$ can be well fitted with a power law with a power index of 0.61 $\pm$ 0.03, similar to that in Orion B (0.67) and NGC 2071 (0.6), indicating that the dense cores are most likely gravitationally bounded rather than pressure confined. The relationship between $M_J$ and $M_{\rm LTE}$ also can be well fitted with a power law with a power index of 0.43 $\pm$ 0.05. Only 11 cores are found to be associated with weak IRAS point sources. Most of the cores
may be starless and have not been affected by star-forming activities.

7. The CMF can be well fitted with a power law for $15 < M_{\text{LTE}}/M_\odot < 200$, whose slope $\alpha = 1.32 \pm 0.08$. The masses of the dense cores are also lognormally distributed. The lognormal behavior of the core mass distribution is determined by internal turbulence, whose distribution also shows a lognormal shape.

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