GASEOUS CO ABUNDANCE—AN EVOLUTIONARY TRACER FOR MOLECULAR CLOUDS

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ABSTRACT

Planck cold clumps are among the most promising objects to investigate the initial conditions of the evolution of molecular clouds. In this work, by combing the dust emission data from the survey of the Planck satellite with the molecular data of $^{12}$CO/$^{13}$CO/C$^{18}$O (1–0) lines from observations with the Purple Mountain Observatory 13.7 m telescope, we investigate the CO abundance, CO depletion, and CO-to-H$_2$ conversion factor of 674 clumps in the early cold cores sample. The median and mean values of the CO abundance are $0.89 \times 10^{-4}$ and $1.28 \times 10^{-4}$, respectively. The mean and median of CO depletion factor are 1.7 and 0.9, respectively. The median value of $X_{\text{CO-to-H}_2}$ for the whole sample is $2.8 \times 10^{20}$ cm$^{-2}$ K$^{-1}$ km$^{-1}$ s. The CO abundance, CO depletion factor, and CO-to-H$_2$ conversion factor are strongly (anti-)correlated to other physical parameters (e.g., dust temperature, dust emissivity spectral index, column density, volume density, and luminosity-to-mass ratio). To conclude, the gaseous CO abundance can be used as an evolutionary tracer for molecular clouds.

Key words: evolution – ISM: abundances – ISM: clouds – ISM: molecules

Online-only material: color figures

1. INTRODUCTION

Carbon monoxide (CO) is the second most abundant molecular species (after H$_2$) in molecular clouds and is often used to determine the column density of molecular hydrogen by assuming a [CO/H$_2$] abundance ratio. Previously, different authors used different [CO/H$_2$] abundance ratios (Wu et al. 2004), ranging from $2.5 \times 10^{-5}$ (Rodriguez et al. 1982) to $10^{-4}$ (Garden et al. 1991). In addition, the observations of $^{12}$CO (1–0) are often used to estimate the entire molecular content of galaxies by applying an empirical CO-to-H$_2$ conversion factor ($X_{\text{CO-to-H}_2} = N_{\text{H}_2}/I_{\text{CO}}$), which is $(1.8 \pm 0.3) \times 10^{20}$ cm$^{-2}$ K$^{-1}$ km$^{-1}$ s for the disk of the Milky Way (Dame et al. 2001). However, the CO-to-H$_2$ conversion factor varies with different methods used to measure the column density of H$_2$ (Pineda et al. 2008). The reliability of using CO as a tracer for molecular mass should be taken seriously because the abundance of gaseous CO is very sensitive to chemical effects such as CO depletion in cold regions.

Toward five low-mass starless cores, Tafalla et al. (2002) found that the abundance of CO near the core center decreases by at least one or two orders of magnitude with respect to the value in the outer core, indicating that a large amount of gaseous CO freezes out onto dust grains in the dense region. In the observations toward 21 IRDCs, the CO depletion factor ($f_D$), which is defined as the ratio of the expected standard gas phase CO abundance to the observed CO abundance, is in between 5 and 78, with a median value of 29 (Fontani et al. 2012). Additionally, the depletion of gas-phase CO seems to increase with density. Caselli et al. (1999) found that the depletion factor is up to $\sim 10$ where the mass surface density is $\Sigma \approx 0.6$ g cm$^{-2}$, while Kramer et al. (1999) found the depletion factor is $\sim 2.5$ for regions with $\Sigma \approx 0.1$–0.15 g cm$^{-2}$. In the observations toward the filamentary IRDC G035.30-00.33, Hernandez et al. (2011) found that the depletion factor increases by about a factor of five as $\Sigma$ increases from $\sim 0.02$ to $\sim 0.2$ g cm$^{-2}$. By combining data from the Five College Radio Astronomy Observatory CO Mapping Survey of the Taurus molecular cloud with extinction data for a sample of 292 background field stars, Whittet et al. (2010) found that the mean ratio of icy CO to gaseous CO increases monotonically from negligible levels for visual extinctions $A_V \lesssim 5$ to $\sim 0.3$ at $A_V = 10$ and $\sim 0.6$ at $A_V = 30$. However, in the survey toward the Gould Belt clouds, only in the cases of starless cores in Taurus and protostellar cores in Serpens is there a correlation between the column densities of the cores and the depletion factor (Christie et al. 2012).

However, previous works are severely subject to relatively small samples and thus they cannot statistically investigate the relationships between gaseous CO abundance and the other physical parameters. In this Letter, we use the early cold cores (ECC) sample to systematically investigate the gaseous CO abundance, CO depletion, and CO-to-H$_2$ conversion factor in molecular clumps. Our results suggest that the gaseous CO abundance strongly (anti-)correlates with dust temperature, dust emissivity spectral index, column density, volume density, and luminosity-to-mass ratio.

2. DATA

The ECC sample is a subset of the Planck Early Release Compact Source Catalogue and contains only the most reliable detections (signal-to-noise ratio $> 15$) of sources with color temperature below 14 K (Planck Collaboration et al. 2011). In the ECC, the photometry is carried out on the original Planck maps by placing an aperture of 5′ radius on top of the detection (Planck Collaboration et al. 2011). The background is estimated using an annulus around the aperture with an inner radius of 5′ and an outer radius of 10′. Temperatures and dust emissivity spectral indexes are derived from a fit to all four bands (IRIS 3 THz and Planck 857, 545, and 353 GHz; Planck Collaboration et al. 2011). The major and minor axes of each source are also obtained from ellipse fit (Planck Collaboration et al. 2011). We extracted the aperture flux density at 857 GHz, the core temperature, core emissivity index, as well as the ellipse major and minor axes of each clump from the ECC catalog.
We have carried out follow-up observations toward 674 ECC clumps with the Purple Mountain Observatory (PMO) 13.7 m telescope. The details of the observations can be found in Wu et al. (2012). The half-power beam width of the telescope at the 115 GHz frequency band is 56′. The main beam efficiency is ∼50%. For each identified 13CO (1–0) component, their kinematic distance and Galactocentric distance were calculated (Wu et al. 2012).

3. RESULTS

3.1. Abundance of Gaseous 12CO

The excitation temperature of 12CO (1–0) can be derived as follows (Garden et al. 1991):

$$T_e = \frac{T_a}{\eta_b} = \frac{\nu}{k} \left[ \frac{1}{\exp(h\nu/kT_{ex}) - 1} - \frac{1}{\exp(h\nu/kT_{bg}) - 1} \right] \times [1 - \exp(-\tau)]f.$$  (1)

Here $T_a$ is the antenna temperature, and $T_e$ is the brightness temperature corrected with beam efficiency $\eta_b$, $k$ is the Planck constant, $\nu$ is the frequency of the observed transition. Assuming 12CO (1–0) emission is optically thick ($\tau \gg 1$) and the filling factor $f = 1$, the excitation temperature $T_{ex}$ can be straightforwardly obtained. Since the Planck cold clumps are clearly extended and are mostly resolved by Planck observations (Planck Collaboration et al., 2011), the assumption of filling factors for gas $f = 1$ is reasonable.

Assuming the 13CO (1–0) and C18O (1–0) lines are optically thin and have the same excitation temperature as 12CO (1–0), the column density of 13CO and C18O under LTE conditions can be obtained as follows (Garden et al. 1991; Pillai et al. 2007):

$$N_{total} = \frac{3h\nu_0}{2\pi^2\mu^2_k} \frac{J(T_{ex})Q(T_{ex})W}{J_e(T_{bg}) - J_e(T_{bg})},$$  (2)

where $\varepsilon_0$ is the dielectric permittivity and $S\mu^2_k$ is the line strength multiplied by the dipole moment along the molecular $g$-axis. $J(T_{ex})$ is defined as (Pillai et al. 2007)

$$J(T_{ex}) = \frac{\exp(E_u/kT_{ex})}{\exp(h\nu/kT_{ex}) - 1},$$  (3)

where $E_u$ is the upper energy level. $J_e(T)$ is defined as (Pillai et al. 2007)

$$J_e(T) = \frac{h\nu/k}{\exp(h\nu/kT) - 1},$$  (4)

where $T_{bg} = 2.73$ is the temperature of the cosmic background radiation.

Then we calculated the peak optical depth $\tau_0$ of 13CO (1–0) and C18O (1–0) from Equation (1) and applied a correction factor $C_{\tau \_LTE}$ = $\tau_0/(1 - \exp(-\tau_0))$ to the column density. The correction factor obtained using the peak optical depth is usually larger than the correction factor obtained using integrals of functions of the optical depth over velocity (Pineda et al. 2010). The difference is especially substantial at high optical depth (Pineda et al. 2010). However, the median peak optical depth of the C18O (1–0) lines is 0.2 and the 13CO (1–0) lines without corresponding C18O (1–0) emission is 0.5, indicating that this problem with the opacity correction is not serious here.

The LTE assumption is another crucial factor of the uncertainties in determining the column density. In the non-LTE case, the excitation temperature of the 13CO (1–0) and C18O (1–0) lines may be very different from that of 12CO (1–0) (Liu et al. 2012b). We applied RADEX (van der Tak et al. 2007), a one-dimensional non-LTE radiative transfer code, to investigate the effect of non-LTE on the determination of the column density of 13CO. The median value of 13CO column density under the LTE assumption is 3.7 × 10^{15} cm^{-2}. The median values of the linewidth of 13CO (1–0) and 12CO (1–0) are 1.1 and 1.8 km s^{-1}, respectively. We fix the volume density of H$_2$ as 2.0 × 10^{3} cm^{-3}, which is the mean value of the whole C3PO sample (Planck Collaboration et al. 2011). Taking the typical values mentioned above and assuming that the relative abundance of 12CO to 13CO is 65, we simulated the emission of 12CO (1–0) and 13CO (1–0) in a parameter space for the kinetic temperature of [5, 20] K using the LVG model in RADEX.

In the left panel of Figure 1, we plot the excitation temperature of 12CO (1–0) and the ratio of the excitation temperature of 13CO (1–0) $T_{ex}^{13}$ to that of 12CO (1–0) $T_{ex}^{12}$ as a function of the kinetic temperature $T_k$. There is a linear relation between the excitation temperature of 12CO (1–0) and the kinetic temperature: $T_{ex}^{12} = 0.89 T_k + 0.73$. The ratio of $T_{ex}^{13}$ to $T_{ex}^{12}$ ranges from 1.13 to 1.26 with a mean value of 1.22, indicating that the LTE assumption overestimates the excitation temperature of 13CO (1–0) by a factor of ∼20%. This leads to an underestimate of the 13CO (1–0) opacity which in turn affects the opacity correction of the column density. From the right panel of Figure 1, one can see that the optical depth of 12CO (1–0) decreases with the kinetic temperature but is much larger than 1. The optical depth of 13CO (1–0) calculated with RADEX also decreases with the kinetic temperature. At low kinetic temperature ($T_k < 8$ K), the 13CO (1–0) emission may become optically thick. We also noted that the optical depth of 13CO (1–0) calculated with RADEX is larger than that calculated under LTE assumption, especially at low kinetic temperatures. Therefore, the opacity correction factor $C_{\tau}$ under the non-LTE condition should be larger than $C_{\tau \_LTE}$. However, the overestimation of the excitation temperature not only affects the optical depth, but also affect the partition function. The partial function $Z$ is given by

$$Z = \sum_{J=0}^{\infty} (2J + 1) e^{-h\nu(J+1/2)} \approx \frac{kT_{ex}}{hB},$$  (5)

Thus, the correction factor on $Z$ due to non-LTE can be defined as $C_Z = (Z_{non\_LTE}/Z_{LTE}) = (T_{ex}^{13}/T_{ex}^{12})$, where $T_{ex}^{13}$ and $T_{ex}^{12}$ are the excitation temperatures of 13CO (1–0) and 12CO (1–0), respectively. In the right panel of Figure 1, we plot $C_Z$ and $C_{\tau}$. $C_{\tau}C_Z/C_{\tau \_LTE}$ is the excitation temperatures of 13CO (1–0) and 12CO (1–0), respectively. In the right panel of Figure 1, we plot $C_Z$ and $C_{\tau}C_Z/C_{\tau \_LTE}$ as function of $T_{ex}^{12}$. We find that $C_Z$ is smaller than 1. $C_{\tau}C_Z/C_{\tau \_LTE}$ is larger than 1 at the lower temperature end, while smaller than 1 at the high temperature end. However, $C_{\tau}C_Z/C_{\tau \_LTE}$ varies slightly around 1 by a factor less than 20%, indicating that the uncertainty in the estimation of the column density due to the non-LTE effect is less than 20%. For this reason, we use the column density estimated under the LTE assumption in the following analysis.

The total column density of H$_2$ ($N_{H_2}$) can be calculated with (Planck Collaboration et al. 2011)

$$N_{H_2} = \frac{S_v}{\Omega_{\nu} \kappa_{\nu} B_{\nu}(T_{bg}) \mu m_H},$$  (6)

where $S_v$ is the flux density at 857 GHz integrated over the solid angle $\Omega_{\nu}$ = ($\pi/4$)$\sigma_{\text{Maj}}$$\sigma_{\text{Min}}$ with $\sigma_{\text{Maj}}$ and $\sigma_{\text{Min}}$ the major
and minor axes of the source, $B_v(T)$ is the Planck function at temperature $T$, $\mu = 2.33$ is the mean molecular weight, and $m_H$ is the mass of atomic hydrogen. The dust opacity $\kappa_\nu = 0.1(\nu/1\text{ THz})^{1.2} \text{ cm}^2 \text{ g}^{-1}$, with $\beta$ the dust emissivity spectral index (Planck Collaboration et al. 2011).

The mass of the clumps is calculated as (Planck Collaboration et al. 2011)

$$M = \frac{S_v D^2}{\kappa_\nu B_v(T)},$$

where $S_v$ is the integrated flux density at 857 GHz and $D$ is the distance.

The Bolometric luminosity is defined by (Planck Collaboration et al. 2011)

$$L = 4\pi D^2 \int \nu S_v d\nu,$$

where $S_v$ is the flux density at frequency $\nu$. The bolometric luminosity, $L$, is integrated over the frequency range $300 \text{ GHz} < \nu < 10 \text{ THz}$, using the modeled spectral energy distributions (SEDs; Planck Collaboration et al. 2011). The luminosity-to-mass ratio of the clumps ranges from $9 \times 10^{-3}$ to $3.5 L_\odot/M_\odot$, with a median value of $0.2 L_\odot/M_\odot$, indicating that the Planck cold clumps are not significantly affected by star forming activities.

The averaged volume density is defined by

$$n_{H_2} = N_{H_2}/\sigma_{\text{Min}}.$$

The resulting volume density ranges from $\sim 10^2$ to $\sim 10^5 \text{ cm}^{-3}$, with a mean value of $5.4 \times 10^3 \text{ cm}^{-3}$, which is slightly larger than the mean value ($2 \times 10^3 \text{ cm}^{-3}$) of the whole C3PO sample (Planck Collaboration et al. 2011).

If the $^{12}$CO (1–0) emission has a corresponding C$^{18}$O (1–0) emission, the column density of $^{12}$CO ($N_{^{12}\text{CO}}$) is converted from $N_{^{13}\text{CO}}$ with the $^{16}$O/$^{18}$O isotope ratio as (Wilson & Rood 1994)

$$\frac{^{16}\text{O}}{^{18}\text{O}} = 58.8 \frac{R}{\text{kpc}} + 37.1,$$

where $R$ is the Galactocentric distance.

Otherwise, we converted $N_{^{13}\text{CO}}$ to $N_{^{12}\text{CO}}$ using the $^{12}$C/$^{13}$C isotope ratio given by (Pineda et al. 2013)

$$\frac{{}^{12}\text{C}}{{}^{13}\text{C}} = 4.7 \frac{R}{\text{kpc}} + 25.05.\quad (11)$$

The above relationship gives a $^{12}$C/$^{13}$C isotope ratio of 65 at $R = 8.5 \text{ kpc}$.

In the sample, about $\sim 30\%$ of clumps have double or multiple velocity components in $^{12}$CO emission and $\sim 16\%$ have double or multiple velocity components in $^{13}$CO emission (Wu et al. 2012). We only considered the velocity components having $^{13}$CO emission in the calculation of the abundance. The observed $^{12}$CO abundance is $[{}^{12}\text{CO}]/[^{13}\text{CO}] = (\sum_i N_{^{12}\text{CO}}/N_{^{13}\text{CO}})$, where $i$ denotes the number of the $^{13}$CO velocity components of each source. One should keep in mind that in the calculation we assume that the dust emission is uniform in the clumps, which may not be the case because in our CO mapping survey (Liu et al. 2012a) and Herschel follow-up surveys (Juvela et al. 2010, 2012) most of the Planck clumps have sub-structures. This insufficiency can be improved in the future by comparing the CO maps with the dust emission maps obtained from higher resolution observations (e.g., Herschel or ground-based telescopes like APEX).

The median and mean values of the observed gaseous $^{12}$CO abundance are $0.89 \times 10^{-4}$ and $1.28 \times 10^{-4}$, respectively.

### 3.2. CO Depletion and CO-to-H$_2$ Conversion Factor

The CO depletion factor, $f_D$, is defined as

$$f_D = \frac{X_{^{12}\text{CO}}^{\text{E}}}{[^{12}\text{CO}]/^{12}\text{CO}},\quad (12)$$

where $X_{^{12}\text{CO}}^{\text{E}}$ is the “expected” abundance of CO.

Taking into account the variation of atomic carbon and oxygen abundances with the Galactocentric distance, the expected $^{12}$CO abundance at the Galactocentric distance $R$ of each source is (Fontani et al. 2012)

$$X_{^{12}\text{CO}}^{\text{E}} = 8.5 \times 10^{-5} \exp(1.105 - 0.13R(\text{kpc})).\quad (13)$$
This relationship gives a canonical CO abundance of \( \sim 8.5 \times 10^{-5} \) in the neighborhood of the solar system (Ferri\`{e}re et al. 1982; Langer et al. 1989; Pineda et al. 2008).

The mean and median of the CO depletion factor are 1.7 and 0.9, respectively. About 53% of Planck cold clumps have a CO depletion factor smaller than 1. Only \( \sim 13\% \) of Planck cold clumps have a CO depletion factor larger than 3 and only about 5.6% larger than 5. It seems that the CO gas in the Planck cold clumps is not severely depleted. Due to the large beam size of the PMO 13.7 m telescope and the Planck satellite, we cannot separate the depleted gas from the non-depleted gas, which should influence the interpretation of the CO depletion measurements. Thus, our measurements indicate that on a clump scale the CO depletion is not significant, in agreement with the fact that on such scales the observed emission arises mostly from low-density, non-depleted gas.

The CO-to-H\(_2\) conversion factor \( X_{\text{CO-to-H}_2} = (N_{\text{H}_2}/\sum l_{\text{CO}}) \), with \( l_{\text{CO}} \) the integrated intensity of the \(^{12}\text{CO} \) (1–0) line. The median value of \( X_{\text{CO-to-H}_2} \) for the whole sample is \( 2.8 \times 10^{20} \) cm\(^{-2}\) K\(^{-1}\) km\(^{-1}\) s. However, CO emission may be saturated at high column density, which will add uncertainties in measuring \( X_{\text{CO-to-H}_2} \). Within the Perseus molecular cloud, the \(^{12}\text{CO} \) emission saturates at \( AV \sim 4 \) mag (Pineda et al. 2008). If we only consider the Planck cold clumps with \( AV < 4 \) mag (\( N_{\text{H}_2} < 3.8 \times 10^{21} \) cm\(^{-2}\)), the median and mean values of \( X_{\text{CO-to-H}_2} \) are 1.7 and 1.9 \( \times 10^{20} \) cm\(^{-2}\) K\(^{-1}\) km\(^{-1}\) s, respectively, which are in agreement with the mean value of \( (1.8 \pm 0.3) \times 10^{20} \) cm\(^{-2}\) K\(^{-1}\) km\(^{-1}\) s for the Milky Way (Dame et al. 2001).

4. DISCUSSION

4.1. The Relationships between Various Physical Parameters

In Figure 2, we investigate the relationships between CO abundance and dust temperature \( (T_d) \), dust emissivity spectral index \( (\beta) \), column density of H\(_2\) \( (N_{\text{H}_2}) \), volume density of H\(_2\) \( (n_{\text{H}_2}) \), luminosity-to-mass ratio \( (L/M) \), as well as the non-thermal one-dimensional velocity dispersion \( (\sigma_{\text{NT}}) \). CO abundance strongly correlates with \( T_d \) and \( L/M \) and anti-correlates with \( \beta \), \( N_{\text{H}_2} \), and \( n_{\text{H}_2} \). These relationships were well fitted with a power-law function \( (y = \eta \cdot x^\beta) \). The coefficients of each model as well as the correlation coefficients \( R^2 \) are displayed in the upper right corner of each panel. There is no correlation between the CO abundance and \( \sigma_{\text{NT}} \), indicating that turbulence has no effect on the fluctuation of CO abundance.

The lower CO abundance for the clumps with lower \( T_d \) and with higher \( N_{\text{H}_2} \), or \( n_{\text{H}_2} \), indicates that CO gas may freeze out significantly toward cold and dense regions. The growth of icy mantles on dust grains could steepen the slope of the dust SED, and thus increase the emissivity spectral index \( \beta \) (Schnee et al. 2010). The anti-correlation between CO abundance and \( \beta \) indicates that a large amount of gaseous CO transforms to icy CO with the growth of icy mantles on dust grains. However, the presence of observational errors makes the anti-correlation between the \( T_d \) and \( \beta \) become unreliable in the C3PO sample (Planck Collaboration et al. 2011). Thus, the relationships between \( \beta \) and the other physical parameters should be taken seriously and tested further by more detailed observations.

In Figure 3, we plot the CO depletion factor \( f_D \) as a function of \( T_d, \beta, N_{\text{H}_2}, n_{\text{H}_2}, L/M, \) and \( \sigma_{\text{NT}} \). The \( f_D \) significantly anti-correlates with \( T_d \) and \( L/M \) and positively correlates with \( \beta, N_{\text{H}_2}, \) and \( n_{\text{H}_2} \). These relationships were well fitted with a power-law function \( (y = \eta \cdot x^\beta) \). In each panel, we divide the data into 10 bins and plot median \( f_D \) in each bin as red filled circles. We find that the median \( f_D \) is larger than 1 in bins with \( T_d < 10.8 \) K or \( \beta > 2.5 \) or \( N_{\text{H}_2} > 6.6 \times 10^{21} \) cm\(^{-2}\) or \( n_{\text{H}_2} > 1.7 \times 10^3 \) cm\(^{-3}\) or \( L/M < 0.16 L_\odot/M_\odot \), indicating that CO gas freeze out in cold and dense regions without significant internal heating. There is also no correlation between the CO depletion factor \( f_D \) and \( \sigma_{\text{NT}} \).

The variation of gaseous CO abundance in molecular clouds should seriously hamper its utility as an estimator of the total hydrogen column density. In Figure 4, we plot the CO-to-H\(_2\) conversion factor \( X_{\text{CO-to-H}_2} \) against \( T_d, \beta, N_{\text{H}_2}, n_{\text{H}_2}, L/M, \) and \( \sigma_{\text{NT}} \). In each panel, the median values of \( X_{\text{CO-to-H}_2} \) in each bin are plotted as red filled circles. There is an inverse correlation between \( X_{\text{CO-to-H}_2} \) and \( T_d \) and \( L/M \), while \( X_{\text{CO-to-H}_2} \) positively correlates to \( \beta, N_{\text{H}_2}, \) and \( n_{\text{H}_2} \). These relationships can be well fitted with power-law functions. There is no correlation between \( X_{\text{CO-to-H}_2} \) and \( \sigma_{\text{NT}} \). We found that the median value of \( X_{\text{CO-to-H}_2} \) is larger than \( 2 \times 10^{20} \) cm\(^{-2}\) K\(^{-1}\) km\(^{-1}\) s in bins with \( T_d < 12 \) K or \( \beta > 2.4 \) or \( N_{\text{H}_2} > 2.6 \times 10^{21} \) cm\(^{-2}\) or \( n_{\text{H}_2} > 2.8 \times 10^3 \) cm\(^{-3}\) or \( L/M < 0.34 L_\odot/M_\odot \).

4.2. Gaseous CO Abundance—An Evolutionary Tracer for Molecular Clouds

The freezing out of gaseous CO onto grain surfaces strongly influences the physical and chemical properties of molecular clouds. As a major destroyer of molecular ions, the CO depletion leads to a change in the relative abundances of major charge carriers (e.g., H\(^+\), N\(_2\)H\(^+\) and HCO\(^+\)), and thus causes variation in the ionizing degree (Caselli et al. 1999; Bergin & Tafalla 2007). Another second-effect induced by CO depletion is deuterium enrichments in cold cores (Caselli et al. 1999; Bergin & Tafalla 2007). These effects make gaseous CO abundance a promising tool to date the evolution of molecular clouds. As discussed in Section 1, a significant fraction of CO molecules is transformed from gas to solid as the gas density increases (Hernandez et al. 2011; Whittet et al. 2010). As a molecular cloud evolves, the density and temperature increase. The bolometric luminosity also increases as the protostars form and evolve in molecular clumps (Emprechtinger et al. 2009). The ratio of bolometric luminosity to submillimeter emission is also used as an effective indicator for protostar evolution. In this work, we found that the relative abundance of gaseous CO significantly anti-correlates with dust temperature and luminosity-to-mass ratio and positively correlates with column density, volume density, and dust emissivity spectral index, indicating that gaseous CO abundance can also serve well as an evolutionary indicator.

One should keep in mind that the Planck cold clumps are cold (<14 K; Planck Collaboration et al. 2011), turbulence-dominated, and have relatively low column densities compared with the other star forming regions (Wu et al. 2012). They are mostly quiescent and lacking star forming activities, indicating that the Planck cold clumps are mostly at the very initial evolutionary stages of molecular clouds (Wu et al. 2012). Thus, the relationships between various physical parameters reported here may be only valid for molecular clouds without significant star forming activities. However, our results indicate that gaseous CO abundance (or depletion) can be used as a tracer for the evolution of molecular clouds. Actually, authors have already used CO depletion to distinguish relatively evolved starless cores from more recently condensed cores (Tafalla & Santiago 2004; Tafalla 2010).
Figure 2. CO relative abundance $[\text{CO}]/\text{H}_2$ as a function of (a) $T_d$, (b) $\beta$, (c) $N_{\text{H}_2}$, (d) $n_{\text{H}_2}$, (e) $L/M$, and (f) $\sigma_{\text{NT}}$. The red line in each panel (also in Figures 3 and 4) is power-law fitting. In each panel (also in Figures 3 and 4), the red filled circles represent the median value in each bin and the size of the green error bars represent the standard error.

(A color version of this figure is available in the online journal.)
Figure 3. CO depletion factor $f_D$ as a function of (a) $T_d$, (b) $\beta$, (c) $N_{H_2}$, (d) $n_{H_2}$, (e) $L/M$, and (f) $\sigma_{NT}$.

(A color version of this figure is available in the online journal.)
Figure 4. CO-to-H$_2$ conversion factor $X_{\text{CO-to-H}_2}$ as a function of (a) $T_d$, (b) $\beta$, (c) $N_{\text{H}_2}$, (d) $n_{\text{H}_2}$, (e) $L/M$, and (f) $\sigma_{NT}$.

(A color version of this figure is available in the online journal.)
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REFERENCES

Bergin, E. A., & Tafalla, M. 2007, ARA&A, 45, 339
Caselli, P., Walmsley, C. M., Tafalla, M., Dore, L., & Myers, P. C. 1999, ApJL, 523, L165
Christie, H., Viti, S., Yates, J., et al. 2012, MNRAS, 422, 968
Dame, T. M., Hartmann, D., & Thaddeus, P. 2001, ApJ, 547, 792
Emprechtinger, M., Caselli, P., Volgenau, I., Stutzki, J., & Wiedner, M. C. 2009, A&A, 493, 89
Fontani, F., Giannetti, A., Beltrán, M. T., et al. 2012, MNRAS, 423, 2342
Ferlet, K., Langer, L., & Wilson, R. 1982, ApJ, 262, 590
Garden, R. P., Hayashi, M., Hasegawa, T., Gatley, I., & Kaifu, N. 1991, ApJ, 374, 540
Hernandez, A. K., Tan, J. C., Caselli, P., et al. 2011, ApJ, 738, 11
Juvela, M., Ristorcelli, I., Montier, L. A., et al. 2010, A&A, 518, L93
Juvela, M., Ristorcelli, I., Pagani, L., et al. 2012, A&A, 541, A12
Kramer, C., Alves, J., Lada, C. J., et al. 1999, A&A, 342, 257
Langer, W. D., Wilson, R. W., Goldsmith, P. F., & Beichman, C. A. 1989, ApJ, 337, 355
Liu, T., Wu, Y., & Zhang, H. 2012a, ApJS, 202, 4
Liu, T., Wu, Y., Zhang, H., & Qin, S.-L. 2012b, ApJ, 751, 68
Pillai, T., Wyrowski, F., Hatchell, J., Gibb, A. G., & Thompson, M. A. 2007, A&A, 467, 207
Pineda, J. E., Caselli, P., & Goodman, A. A. 2008, ApJ, 679, 481
Pineda, J. L., Goldsmith, P. F., Chapman, N., et al. 2010, ApJ, 721, 686
Pineda, J. L., Langer, W. D., Velusamy, T., & Goldsmith, P. F. 2013, A&A, 554, 103
Planck Collaboration, Ade, P. A. R., Aghanim, N., Arnaud, M., et al. 2011, A&A, 536, 23
Rodríguez, L. F., Carral, P., Moran, J. M., & Ho, P. T. P. 1982, ApJ, 260, 635
Schnee, S., Enoch, M., Noriega-Crespo, A., et al. 2010, ApJ, 708, 127
Tafalla, M. 2010, in Highlights of Spanish Astrophysics VI, Proc. IX Scientific Meeting of the Spanish Astronomical Society (SEA), ed. M. R. Zapatero Osorio, J. Gorgas, J. Maz Apellániz, J. R. Pardo, & A. Gil de Paz (Madrid: SEA), 442
Tafalla, M., Myers, P. C., Caselli, P., Walmsley, C. M., & Comito, C. 2002, ApJ, 569, 815
Tafalla, M., & Santiago, J. 2004, A&A, 414, L53
van der Tak, F. F. S., Black, J. H., Schöier, F. L., Jansen, D. J., & van Dishoeck, E. F. 2007, A&A, 468, 627
Whittet, D. C. B., Goldsmith, P. F., & Pineda, J. L. 2010, ApJ, 720, 259
Wilson, T. L., & Rood, R. T. 1994, ARA&A, 32, 191
Wu, Y., Liu, T., Meng, F., et al. 2012, ApJ, 756, 76
Wu, Y., Wei, Y., Zhao, M., et al. 2004, A&A, 426, 503