Star Formation Conditions in a Planck Galactic Cold Clump, G108.84–00.81

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Abstract

We present the results from a series of ground-based radio observations toward a Planck Galactic Cold Clump (PGCC) G108.84–00.81, which is located in one curved filamentary cloud in the vicinity of an extended H II region Sh2-152 and SNR G109.1-1.0. PGCC G108.84–00.81 is mainly composed of two clumps, “G108–N” and “G108–S”. In the 850 μm dust continuum emission map, G108–N is shown as one component while G108–S is fragmented into four components. There is no infrared source associated with G108–N, while there are two infrared sources (IRS 1 and IRS 2) associated with G108–S. The total mass of G108–N is larger than the Jeans mass, suggesting that G108–N is gravitationally unstable and a potential place for a future star formation. The clump properties of G108–N and G108–S such as the gas temperature and the column density, are not distinctly different. However, G108–S is slightly more evolved than G108–N, if considering the CO depletion factor, molecular abundances, and association with infrared sources. G108–S seems to be affected by the compression from Sh2-152, while G108–N is relatively protected from the external effect.

Key words: ISM: clouds – methods: observational – stars: formation

1. Introduction

Expanding H II regions or supernova explosions can strongly influence their surrounding interstellar medium (ISM) and regulate star formation. The shocks induced in H II regions or supernova remnants (SNRs) may gather surrounding molecular gas to form dense shells, which may collapse to form stars later (Elmegreen & Lada 1977; Whitworth et al. 1994). This so-called “collect and collapse” process can self-propagate and lead to sequential star formation (Elmegreen & Lada 1977; Whitworth et al. 1994). The “collect and collapse” model was first developed to explain the age sequence of spatially distinct OB subgroups in nearby OB associations such as Orion OB1 (Elmegreen & Lada 1977). More and more evidence in recent observations indicates that new generations of stars can form in shells or pillar structures surrounding H II regions (see Liu et al. 2012b; Dale et al. 2015; Liu et al. 2015, 2016a and the references therein). Thompson et al. (2012) estimated that the fraction of massive stars in the Milky Way formed by triggering processes could be between 14% and 30%, using statistical studies of young stellar objects (YSOs) projected against the rims of Spitzer infrared bubbles.

However, recent numerical simulations suggest that stellar feedback from massive stars always results in a lower star formation efficiency and most signs, such as the ages and geometrical distributions of stars relative to the feedback source or feedback-driven structure (e.g., shells, pillar structures), may not be substantially helpful for distinguishing triggered star formation from spontaneous star formation (Dale et al. 2012, 2015). Studying the conditions (e.g., temperature, density, velocity, chemistry) of dense cores near H II regions may be helpful to distinguish triggered star formation from spontaneous star formation. The dense cores should be externally heated and compressed by H II regions if their star formation are triggered.

The Planck satellite survey provides a catalog containing 13,188 Planck Galactic cold clumps (PGCCs; Planck Collaboration et al. 2016). The clumps have dust temperatures lower than 14 K, indicating that PGCCs correspond to the coldest portion of the ISM. A survey in the J = 1–0 lines of 12CO, 13CO, and C18O toward 674 PGCCs has been carried out using the 13.7 m telescope of Purple Mountain Observatory (PMO; Wu et al. 2012; Liu et al. 2013; Zhang et al. 2016). Nearly 98% of the clumps have excitation temperatures (T ex) of CO 1–0 that are lower than 16 K. Clumps with excitation temperatures above 16 K are located in star-forming regions, suggesting that the high T ex is related to star-forming activities (Wu et al. 2012). A large fraction of PGCCs have temperatures that are lower than the typical temperatures of infrared dark clouds (IRDCs; 15 K; Pillai et al. 2006), which are known to be the earliest phase of star formation (Carey et al. 1998; Simon et al. 2006). This suggests that PGCCs may represent an earlier evolutionary stage than IRDCs. To investigate the initial conditions of star formation, especially to study the environmental effects on dense core formation, a legacy survey of PGCCs using the Submillimeter Common User Bolometer Array-2 (SCUBA-2) on board the James Clerk Maxwell Telescope (JCMT) at the East Asia Observatory, “SCUBA-2 Continuum Observations of Pre-protostellar Evolution (SCOPE)”, is in progress (T. Liu et al. 2017, in preparation).

PGCC G108.84–00.81 is observed as part of SCOPE. It has an excitation temperature of ~15 K and an H2 column density of 2.0 × 1022 cm−2 (Wu et al. 2012). Hereafter, we will refer to the region covered by PMO observations (500″ × 500″) as PGCC G108.84–00.81 and the central part of PGCC

https://tiki-index.php

https://tiki-topscope.asiaa.sinica.edu.tw/tiki/tiki-index.php

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Table 1

| Molecular line | \( \nu \) [GHz] | Beam FWHM [arcsec] | \( \eta_{\text{mb}}^a \) | Telescope |
|----------------|-----------------|---------------------|-----------------|-----------|
| HCN 1–0       | 88.631847       | 29                  | 0.81            | IRAM 30 m |
|                | 32              | 0.37                | KVN 21 m (Yonsei) |
|                | 33              | 0.43                | KVN 21 m (Ulsan) |
|                | 32              | 0.36                | KVN 21 m (Tanna) |
| HCO\(^+\) 1–0 | 89.185526       | 29                  | 0.81            | IRAM 30 m |
| N\(_2\)H\(^+\) 1–0 | 93.173776    | 20.4                | 0.54            | NRO 45 m |
| CO 1–0        | 115.271202      | 60                  | 0.67            | PMO 13.7 m |
| \(^{13}\)CO 1–0 | 110.201354   | 60                  | 0.67            | PMO 13.7 m |
| C\(^{18}\)O 1–0 | 109.782176   | 60                  | 0.67            | PMO 13.7 m |
| CO 2–1        | 230.538000      | 32.5                | 0.76            | CSO 10 m |
| \(^{13}\)CO 2–1 | 226.398684  | 32.5                | 0.76            | CSO 10 m |
| C\(^{18}\)O 2–1 | 219.560358   | 32.5                | 0.76            | CSO 10 m |
| NH\(_3\) (1, 1) | 236.94945      | 40                  | 0.79            | Effelsberg 100 m |

Note.

\(^a\) The main beam efficiencies.

G108.84–00.81 covered by SCUBA-2 as G108. An SNR, SNR G109.1–1.0, and an H\(^{\text{II}}\) region, Sh2-152, are located near PGCC G108.84–00.81. Therefore, PGCC G108.84–00.81 is an ideal target to investigate the environmental effect on the initial conditions of star formation.

In this study, we investigate the interaction between PGCC G108.84–00.81 and its surrounding environments with CO line observations. The chemical and physical properties of G108 are also studied in detail through a series of observations in both continuum and molecular lines. In Section 2, our observations toward PGCC G108.84–00.81 and G108 are summarized. Results and an analysis are presented in Sections 3 and 4, respectively. We discuss the environmental influence on the star formation in PGCC G108.84–00.81 in Section 5. Finally, a summary of the study is given in Section 6.

2. The Data

A series of observations toward PGCC G108.84–00.81 has been conducted with ground-based radio telescopes. The reduction process of molecular line data was done using the GILDAS/CLASS\(^8\) package. A summary of the molecular line observations is provided in Table 1.

2.1. PMO Observations

The CO 1–0, \(^{13}\)CO 1–0, and C\(^{18}\)O 1–0 line mapping observations of PGCC G108.84–00.81 were carried out using the 13.7 m radio telescope of the PMO at De Ling Ha in 2011 May. The on-the-fly (OTF) observing mode was applied. More details of the OTF observations with the PMO 13.7 m telescope toward Planck cold clumps can be found in Liu et al. (2012a). The beam FWHM is \(\sim 52''\) at 115 GHz and the beam efficiency is \(\sim 0.45\). The newly installed nine-beam array receiver in the single-sideband mode was used. The Fast Fourier Transform Spectrometer (FFTS), which has 16,384 channels in a total bandwidth of 1 GHz, was used. The velocity resolution of the CO 1–0 line is 0.16 km s\(^{-1}\) and that of both \(^{13}\)CO 1–0 and C\(^{18}\)O 1–0 is 0.17 km s\(^{-1}\). CO 1–0 was observed at the upper sideband and \(^{13}\)CO 1–0 and C\(^{18}\)O 1–0 were observed simultaneously at the lower sideband. The map size for further analysis is about 480'' \(\times\) 480''.

2.2. CSO Observations

Molecular line observations of PGCC G108.84–00.81 were carried out with the 10 m radio telescope of the Caltech Submillimeter Observatory (CSO) in 2014 January (see Meng et al. 2017, in preparation). We mapped the CO 2–1, \(^{13}\)CO 2–1, and C\(^{18}\)O 2–1 lines toward G108. The Sidecab receiver and the FFTS2 spectrometer were used. The velocity resolution is about 0.35 km s\(^{-1}\). The beam FWHM is 32'' and the beam efficiency is 0.76 at 230 GHz. A map area of 120'' \(\times\) 120'' centered at G108 is selected for further analysis because of apparent higher noise levels at map edges.

2.3. NRO Observations

We also observed the HCO\(^+\) 1–0 and HCN 1–0 lines toward the northern part of G108 with the 30 m radio telescope of the Institut de Radioastronomie Millimétrique (IRAM) in 2014 May. The velocity resolution is 0.33 km s\(^{-1}\). The beam FWHM and beam efficiency are \(\sim 29''\) and 0.81, respectively. The map size is 80'' \(\times\) 80''.

2.4. IRAM Observations

Observations of the northern part of G108 in the NH\(_3\) (1, 1) line were carried out with the 100 m radio telescope of Effelsberg in 2015 April. The NH\(_3\) (1, 1) line was observed with the 1.3 cm double beam secondary focus receiver. The beam FWHM and beam efficiency are \(\sim 38''\) and 0.79, respectively. The velocity resolution is 0.15 km s\(^{-1}\). An area of 80'' \(\times\) 80'' was mapped.

2.5. Effelsberg Observations

Single-point observations of the HCN 1–0 line were carried out toward the peak positions of the 850 \(\mu\)m dust continuum map in 2016 June with the Korean VLBI Network (KVN) 21 m telescopes (Kim et al. 2011). Observations were conducted at the three stations of KVN (Yeonsei, Ulsan, and Tamna). We used the digital spectrometer with 32 MHz in bandwidth divided into 4096 channels, providing a velocity resolution of \(\sim 0.2\) km s\(^{-1}\) at 88 GHz. The averaged beam FWHM and beam efficiency at the three stations are \(\sim 32''\) and \(\sim 0.39\) at 88 GHz.

8 See https://www.iram.fr/IRAMFR/GILDAS/doc/html/class-html/class.html
2.7. JCMT Observations

The 850 $\mu$m continuum emission map was obtained with JCMT/SCUBA-2 in 2015 May in the “CV Daisy” mapping mode, which is optimized for point sources. The CV Daisy is designed for small compact sources providing a deep 3$''$ region in the center of the map but coverage out to beyond 12$'$ (Bintley et al. 2014). All the SCUBA-2 850 $\mu$m continuum data were reduced using an iterative map-making technique (Chapin et al. 2013). Specifically, the data were all run with the reduction tailored for compact sources, filtering out scales larger than 200$''$ on a 4$''$ pixel scale. The beam FWHM of SCUBA-2 at 850 $\mu$m is $\sim$13$''$. The field of view of SCUBA-2 is about 8$'$ at 850 $\mu$m. However, an area of about 5$'\times5'$ entered at PGCC G108.84–00.81 is used for further analysis.

Molecular line observations in HCO$^+$ 4–3 toward the northern part of G108 were also carried out using the JCMT Heterodyne Array Receiver Program (HARP) system in 2015 September. HARP is a single-sideband array receiver composed of 16 SIS.
mixers. The beam FWHM at 350 GHz is ∼14″ and the beam efficiency is 0.64. The mapping area is about 50″ × 50″.

We used the "ORAC-DR" pipeline in STARLINK for imaging data reduction.

2.8. Infrared Data

We also included images from the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010). We gathered available photometric data of YSO candidates in G108 from several catalogs. The data at 3.4, 4.6, 12, and 22 μm are from the ALLWISE catalog including 2MASS data. The data at 9 and 18 μm are from the AKARI/IRC Point Source Catalogue (AKARIPSC; Ishihara et al. 2010).

3. Results

3.1. Filament Structure in the CO 1–0 and 13CO 1–0 Maps

PGCC G108.84–00.81 is surrounded by dynamically active regions such as an SNR, SNR G109.1–1.0, and an H II region, Sh2-152. According to the Planck Early Cold Clump catalog note, there is one IRAS point source, IRAS 22565+5839, associated with PGCC G108.84–00.81 within 5 arcmin from the center of PGCC G108.84–00.81. One large filament structure is shown in the integrated intensity map of CO 1–0 (Figure 1). This filament structure is largely divided into three parts: the northeast region associated with a star (Yung et al. 2014), IRAS 22576+5843, the southern region directly linked to Sh2-152, and the central part defined as G108, containing IRAS 22565+5839. As shown in the 13CO 1–0 map in Figure 2, G108 is composed of two components. One is located northeast (NE) from the central position and the other is located southwest (SW). We use "G108–N" to indicate the NE component and "G108–S" for the SW component.

The systemic velocity of –49.6 km s⁻¹ has been measured by Gaussian-fitting the C₁⁸O 1–0 spectra toward G108. The nearby H II region, Sh2-152, has a similar systemic velocity to G108. We adopt the distance to PGCC G108.84–00.81 as 3.21 ± 0.21 kpc from the distance estimation of Sh2-152 by Ramirez Alegría et al. (2011), based on near-infrared extinction. According to the moment 1 maps presented in Figure 2, a
small velocity gradient is present at the SW part of PGCC G108.84–00.81.

3.2. Two Clumps within G108

Figure 3 presents the integrated intensity maps of CO 2–1 and $^{13}$CO 2–1 overlaid onto their Moment 1 maps obtained at the CSO. G108–N and G108–S seem separated in the CO 2–1 map. The integrated intensity map of $^{13}$CO 2–1 presents more fragmented structures than that of CO 2–1. The component with a blueshifted velocity with regard to the systemic velocity ($\sim -50.5 \text{ km s}^{-1}$) is shown west of G108–S. The redshifted velocity components are located along the eastern edge of the filament in the $^{13}$CO 2–1 map.

The spectra of CO isotopologues obtained with the CSO telescope toward G108–N and G108–S are shown in Figure 4. The central velocities of three lines are coincident with each other. Figure 5 shows the integrated intensity ratios, CO 2–1/CO 1–0 and $^{13}$CO 2–1/$^{13}$CO 1–0. The enhancements of CO 2–1/CO 1–0 ratios (>1) are known toward molecular clouds associated with SNRs (Seta et al. 1998). However, in G108, the $^{13}$CO 2–1/$^{13}$CO 1–0 ratio is the most enhanced at the southern edge of G108–S, which is close to the H II region.

In Figure 6, the 850 $\mu$m dust continuum emission map is overlaid onto the WISE 12 $\mu$m image. Dust continuum emission toward G108 is also largely divided into two parts (G108–N and G108–S) as molecular line emission. The distribution of dust continuum emission of G108–N shows a cometary structure. The head is located NE from the center, with a tail structure extended SW. Highly fragmented structure appears in G108–S. At least four components exist in G108–S. G108–S1 to S4 are assigned along with right ascension. As shown in the integrated intensity maps of CO 2–1, $^{13}$CO 2–1, and C$^{18}$O 2–1 overlaid onto the 850 $\mu$m dust continuum emission map (Figure 7), the intensity peaks of all three lines are off from that of the dust continuum.

3.3. A Starless Clump, G108–N

To investigate the molecular environments of the starless clump, G108–N, single-dish observations were conducted. The integrated intensity maps of HCO$^+$ 1–0 and HCN 1–0 obtained with the IRAM 30 m telescope are shown in Figure 8. The HCO$^+$ 1–0 and HCN 1–0 show a similar distribution to each other and also to the distribution of 850 $\mu$m continuum emission. The peak positions of HCO$^+$ 1–0 and HCN 1–0 are slightly shifted from that of the 850 $\mu$m continuum emission peak. The emission of the two lines distributes along the cometary structure in the NE–SW direction. The head to the NE with a tail extended SW is shown in HCO$^+$ 1–0 and HCN 1–0 maps, while the HCO$^+$ 4–3 obtained with the JCMT/HARP shows a compact distribution near the head part (Figure 8(c)). This cometary structure is also shown in the integrated intensity map of NH$_3$ (1, 1) obtained with the Effelsberg 100 m telescope (Figure 9).

The line profiles of all observed molecular lines toward the 850 $\mu$m dust continuum peak of G108–N are presented in Figure 10. The centroid velocities of all lines are consistent.

4. ANALYSIS

4.1. IR Source in Association with G108

G108–N has no associated infrared (IR) source. On the other hand, two IR sources associated with G108–S1 and G108–S2 are detected at all four bands of WISE (Figure 6). Hereafter, the IR sources associated with G108–S1 and G108–S2 are called IRS 1 and IRS 2, respectively. IRS 22565+5839, an associated IRAS point source from the PGCC catalog, is located at the center of the projected separation of IRS 1 and IRS 2, suggesting that the IRAS source is resolved at the WISE 12 $\mu$m with a higher spatial resolution ($\sim 6''$). IRS 1 and IRS 2 are identified as YSO candidates based on the diagnostic color–color and color–magnitude diagrams (see Figure 11).
the YSO identification schemes presented by Koenig & Leisawitz (2014).

The evolutionary stages of IRS 1 and IRS 2 are classified by their spectral indices and bolometric temperatures. A spectral index $\alpha$ is derived by fitting the photometric data in the wavelength range from 2 to 24 $\mu$m as (Evans et al. 2009)

$$\alpha = \frac{d \log(\lambda S(\lambda))}{d \log(\lambda)}.$$
Figure 8. Integrated intensity maps (contours) of (a) HCO$^+$ 1–0, (b) HCN 1–0, and (c) HCO$^+$ 4–3 on top of the 850 $\mu$m dust continuum map of G108–N (grayscale). Contour intervals are 10% of each peak intensity and range from 40% to 90%. The grayscale levels are 20%–90% of the peak intensity in steps of 10%. The peak intensities of HCO$^+$ 1–0, HCN 1–0, and HCO$^+$ 4–3 are 4.7, 5.6, and 0.8 K km s$^{-1}$, respectively, while the peak intensity of 850 $\mu$m dust continuum is 232 mJy beam$^{-1}$. The filled circle and the open circle in the bottom left of each panel denote the respective beam FWHMs of JCMT/SCUBA-2 and Effelsberg 100 m.

Figure 9. Integrated intensity map of NH$_3$ (1, 1) (contours) on top of the 850 $\mu$m map of G108–N (grayscale). Contour intervals are 10% of each peak intensity and range from 40% to 90%. The grayscale levels are 20%–90% of the peak intensity in steps of 10%. The peak integrated intensity of NH$_3$ (1, 1) is 0.54 K km s$^{-1}$, while the peak intensity of 850 $\mu$m dust continuum is 232 mJy beam$^{-1}$. The filled circle and the opened circle in the bottom left of each panel denote the respective beam FWHMs of JCMT/SCUBA-2 and Effelsberg 100 m.

Here, $S(\lambda)$ is the flux density at the wavelength $\lambda$. The photometric data used to estimate the spectral index are listed in Table 2. The spectral indices of IRS 1 and IRS 2 are 0.61 and 0.48, respectively. Using the classification scheme from Evans et al. (2009) (i.e., Class I for $0.3 \leq \alpha < 1$, Flat for $-0.3 \leq \alpha < 0.3$, Class II for $-1.6 \leq \alpha < -0.3$, and Class III for $\alpha < -1.6$), both are classified as Class I sources.

The bolometric luminosities ($L_{\text{bol}}$) and bolometric temperatures ($T_{\text{bol}}$) of the two YSO candidates are also calculated. The $L_{\text{bol}}$ of IRS 1 and IRS 2 are 27 and 30 $L_\odot$, respectively, indicating these two sources are low-mass YSOs ($L_{\text{bol}} < 50 L_\odot$). IRS 1 and IRS 2 have $T_{\text{bol}}$ of 341 K and 614 K, respectively. Following the classification criteria from Myers & Ladd (1993) (i.e., Class 0 for $T_{\text{bol}} < 70$ K, Class I for $70 K < T_{\text{bol}} \leq 650$ K, and Class II for $650 K < T_{\text{bol}} \leq 2800$ K), both are also classified as Class I sources. The CO outflows, which are commonly associated with embedded Class 0/I sources, are not detected in these two Class I sources. Higher resolutions and better sensitivities may reveal the associated outflows. The bolometric luminosities, the bolometric temperatures, and the spectral indices of the two IR sources are listed in Table 3.

4.2. Clump Properties of G108–N and G108–S

4.2.1. Gas Temperature

We assume that the $^{12}$CO line is optically thick and all levels are in local thermodynamic equilibrium (LTE) to derive its excitation temperature (Liu et al. 2013). Therefore, the excitation temperatures ($T_{\text{ex}}$) in all levels and the kinetic temperature ($T_{\text{kin}}$) are the same. We also assume that dust and gas are well coupled ($T_{\text{ex}} = T_{\text{kin}} = T_{\text{dust}}$).

The excitation temperature is derived from the brightness temperature of CO 2–1, which is optically thick ($\tau \gg 1$). The expression for the brightness temperature, $T_b$, is

$$T_b = [J_b(T_{\text{ex}}) - J_b(T_{\text{dust}})](1 - e^{-\tau_b})f,$$

where $J_b = h\nu_b/k(e^{h\nu_b/kT_b} - 1)^{-1}$, $\tau_b$ is optical depth, and $f$ is the beam-filling factor and is assumed as unity.

We compared the calculated $T_{\text{ex}}$ with the results of the previous studies. The mean $T_{\text{ex}}$ toward G108–N and G108–S are 13.4 K and 12.5 K, respectively, which are consistent with the $T_{\text{dust}}$ (11.9 ± 2.8 K) of PGCC G108.84–00.81 from the Planck PGCC catalog (Planck Collaboration et al. 2016). $T_{\text{kin}}$ from the ammonia observations (Tatematsu et al. 2017) of G108–N and G108–S are 14.3 K and <19.1 K, respectively. The calculated $T_{\text{ex}}$ is also consistent with this $T_{\text{kin}}$, suggesting that our LTE assumption is reliable.

4.2.2. H$_2$ Column Density Derived from C^{18}O 2–1 Line

We calculate the H$_2$ column density from the C$^{18}$O line assuming LTE and the same excitation temperature as CO. The column density, $N_{\text{H}_2}$, under the assumption of optically thin emission ($\tau \ll 1$), can be estimated with the integrated intensity...
of the line integral \( W \) (K km s\(^{-1}\)) (Schnee et al. 2007) as

\[
N_{\text{thin}} = \frac{8\pi W}{\lambda^3 \Lambda} \frac{g_l}{g_u} \frac{1}{J_l(T_{\text{ex}}) - J_r(T_{\text{bg}})} \times \frac{1}{1 - \exp(-h\nu/kT_{\text{ex}})} \frac{Q_{\text{rot}}}{g_l \exp(-E_l/kT_{\text{ex}})} \text{ cm}^{-2},
\]

where \( \nu \) and \( \lambda \) are the frequency and wavelength of the transition, \( A \) is the Einstein coefficient, \( g_l \) and \( g_u \) are the statistical weights of the lower and the upper levels, \( J_l(T) = \frac{h\nu}{k} \). \( Q_{\text{rot}} \) is the partition function, and \( E_l \) is the energy of the lower level. The energy of each level is given by \( E_J = J(J + 1)\hbar B \), where \( B \) is the rotational constant.

However, in some cases, \(^{18}\)O 2–1 is not perfectly optically thin. An optical depth can be corrected in the calculation of column density using the correction factor, \( C_{\tau} \), as long as \( \tau \leq 2 \) (Schnee et al. 2007).

\[
C_{\tau} = \frac{\tau}{1 - e^{-\tau}}.
\]

The optical depth (\( \tau \)) can be found from

\[
\tau = -\ln \left[ 1 - \frac{T_{\text{thin}}}{J(T_{\text{ex}}) - J(T_{\text{bg}})} \right]
\]

where \( T_{\text{thin}} \) is the beam-corrected brightness temperature of the given line. The final column density corrected for the optical depth is

\[
N = N_{\text{thin}} \cdot C_{\tau}.
\]

Finally, the H\(_2\) column density is derived by dividing the abundance of the molecule \( x \), \( X(x) \):

\[
N(H_2) = \frac{N(x)}{X(x)} \text{ cm}^{-2}.
\]

The \(^{18}\)O abundance, \( X(^{18}\text{O}) \), of \( 4.8 \times 10^{-7} \) is used (Lee et al. 2003).

The sizes of G108–N and G108–S are defined as \( R = \sqrt{a \cdot b} \), where \( a \) and \( b \) are the major and minor axes of deconvolved FWHM size measured at the 50% contours of the \(^{18}\)O 2–1 emission region. The mean H\(_2\) column densities of G108–N and G108–S within the clump size are \( 6.7 \times 10^{21} \) and \( 1.0 \times 10^{22} \) cm\(^{-2}\), respectively. Derived parameters are listed in Table 4.

4.2.3. H\(_2\) Column Density Derived from Dust Continuum Emission

The molecular gas column density can be calculated with the dust continuum flux, \( S_\nu \), using

\[
N(H_2) = \frac{S_\nu}{\mu m_\text{H} \kappa_\nu B_\nu(T_{\text{dust}})\Omega} \text{ cm}^{-2},
\]

where \( \mu \) is the mean molecular weight, \( m_\text{H} \) is the atomic hydrogen mass, \( \kappa_\nu \) is the mass opacity coefficient, and \( B_\nu(T_{\text{dust}}) \) is the Planck function with a dust temperature (\( T_{\text{dust}} \)). The dust temperature \( T_{\text{dust}} \) is adopted from the gas temperature derived in Section 4.2.1. The aperture solid angle, \( \Omega = \pi \theta^2 / 4 \ln 2 \), is a circular Gaussian aperture where \( \theta \) is the beam FWHM. We use the 850 \( \mu \)m dust continuum emission to calculate the H\(_2\) column density. The mass opacity coefficient of 0.018 cm\(^2\) g\(^{-1}\) (Ossenkopf & Henning 1994) is used, assuming a gas-to-dust ratio of 100. In order to make a consistent comparison, the 850 \( \mu \)m data have been smoothed to the \(^{18}\)O 2–1 resolution. A beam FWHM of 32\( ^\prime\)5 is used to calculate the aperture solid angle. Within the clump size, the mean H\(_2\) column densities of G108–N and G108–S are \( 5.6 \times 10^{21} \) and \( 8.4 \times 10^{21} \) cm\(^{-2}\), respectively. Derived parameters are also listed in Table 4.

4.2.4. Total Mass and Kinematics

Dust continuum emission at 850 \( \mu \)m is known as one of the best tracers of the total cloud mass because it is optically thin. Therefore, we derive the total (gas+dust) masses, \( M_{\text{total}} \), of
G108–N and G108–S, using

\[ M_{\text{total}} = \frac{S_d d^2}{\kappa_d B_d(T_{\text{dust}})} \]

where \( S_d \) is the 850 \( \mu \)m integrated flux and \( d \) is the distance (3.21 \( \pm \) 0.21 kpc; Ramírez Alegria et al. 2011). We adopt the same coefficient as those used in Equation (8). \( T_{\text{dust}} \) for G108–N and G108–S are adopted from the gas temperatures derived in Section 4.2.1 as 13.4 and 12.5 K, respectively. Their derived total masses are listed in Table 5. The total mass of G108–N is larger than the sum of the masses of G108–S1 to S4; the total mass of G108–N is 386 \( \pm \) 2 \( M_\odot \), indicative of a massive starless clump.

To investigate whether the clump is gravitationally unstable, and thus, the possibility of future star formation, we compare its Jeans mass with the total clump mass. The gas in molecular clouds is supported against gravitational collapse by turbulence and magnetic field as well as the thermal pressure. The Jeans mass can be derived by

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

taking into account the thermal and turbulent support (Hennebelle & Chabrier 2008), where \( n = N(\text{H}_2)/2R \) is the volume density of \( \text{H}_2 \). The effective kinematic temperature, \( T_{\text{eff}} \), is given by

\[ T_{\text{eff}} = C_{s,\text{eff}}^2 \mu m_1/k \]

with the effective sound speed \( C_{s,\text{eff}} \). The \( C_{s,\text{eff}} \) including thermal and turbulent support can be derived by

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

The one-dimensional thermal \( (\sigma_T) \) and non-thermal \( (\sigma_{NT}) \) velocity dispersions can be calculated as

\[ \sigma_T = \left[ \frac{kT_{\text{ex}}}{m_1 \mu} \right]^{1/2}, \]

\[ \sigma_{NT} = \left[ \sigma_{C8O}^2 - \frac{kT_{\text{ex}}}{m_c^{18} O} \right]^{1/2}, \]
Notes.

a The size of the semimajor axis.
b The size of the semiminor axis.

where \( k \) is Boltzmann’s constant. \( \sigma_{\text{ex}}^{2} = \Delta V_{\text{ex}}^{2} / 8 \ln(2) \) is the one-dimensional velocity dispersion of \( \text{C}^{18}\text{O} \) 2–1 and \( m_{\text{ex}} \) is the mass of \( \text{C}^{18}\text{O} \). The calculated Jeans mass is 299 \( M_{\odot} \), with \( n = 1.0 \times 10^{4} \text{cm}^{-3} \), \( T_{\text{eff}} = 222 \text{ K} \), \( \sigma_{T} = 0.20 \text{ km s}^{-1} \), and \( \sigma_{\text{NT}} = 0.79 \text{ km s}^{-1} \). The total mass of G108–N (386 \( M_{\odot} \)) is larger than \( M_{J} \), suggesting that G108–N is gravitationally unstable (i.e., a prestellar clump).

4.3. Chemical Status of Two Clumps

4.3.1. CO Depletion

According to the comparison between the integrated intensity distributions of molecular lines and the dust continuum, the molecular line emission peaks are slightly shifted SW from the dust continuum emission peak. This might be caused by the molecular depletion at the dust continuum peak (Lee et al. 2003). We compare the \( \text{H}_{2} \) column densities, \( N(\text{H}_{2}) \), derived from \( \text{C}^{18}\text{O} \) 2–1 and the 850 \( \mu \text{m} \) dust continuum emission to derive the CO depletion factor, which is defined as:

\[
D_{\text{CO}} = \frac{N(\text{H}_{2})_{\text{dust}}}{N(\text{H}_{2})_{\text{CO}}}.
\]  

The maximum depletion factor of G108–N is about 1.8, while that of G108–S is about 4. The low CO depletion suggests that the dynamical timescales of G108–N and G108–S are not very large, that is, the high-density clumps might have formed recently. However, we cannot rule out an artificial effect; the \( \text{H}_{2} \) column density derived from dust continuum emission could be underestimated because the extended structure is possibly filtered out during the reduction process.

4.3.2. Molecular Abundances

Figure 12 shows the averaged spectra within the 50% contour of the integrated intensity peak of \( \text{N}_{2}\text{H}^{+} \) 1–0 toward G108–N and G108–S obtained with the NRO 45 m telescope; the \( \text{N}_{2}\text{H}^{+} \) 1–0 emission is spatially distributed in a larger area than the beam FWHM (20\(^{\prime}\)4). The \( \text{N}_{2}\text{H}^{+} \) 1–0 line is fitted using the hyperfine structure (HFS) fitting method in GILDAS/CLASS to determine \( T_{\text{ex}} \) and optical depth, \( \tau \). In both clumps, the \( \text{N}_{2}\text{H}^{+} \) 1–0 lines are optically thin (\( \tau < 0.1 \)). The derived \( T_{\text{ex}} \) of G108–N and G108–S are 3.7 and 3.3 K, respectively, which are very low, compared to the \( T_{\text{ex}} \) of \( \text{CO} \) in G108–N (13.4 K) and G108–S (12.5 K). We also derived the \( T_{\text{ex}} \) of HCN by fitting the HFS of the HCN 1–0 line. The spectra of HCN 1–0 at each position are presented in Figure 13. The \( T_{\text{ex}} \) of HCN in G108–N and G108–S are 3.6 and 3.8 K, respectively, which are similar to those of \( \text{N}_{2}\text{H}^{+} \). The optical depths at all five positions are less than 1.

\( \text{N}_{2}\text{H}^{+} \) and HCN seem sub-thermally excited, so we derive the column densities of \( \text{N}_{2}\text{H}^{+} \) and HCN using a non-LTE radiative transfer code, RADEX (van der Tak et al. 2007). We assume that \( T_{\text{ex}} \) is equal to the \( T_{\text{ex}} \) derived from \( \text{C}^{18}\text{O} \) 2–1 for G108–N and G108–S. The mean \( \text{H}_{2} \) volume density is derived from the 850 \( \mu \text{m} \) dust continuum emission. For the \( \text{N}_{2}\text{H}^{+} \) analysis, the 850 \( \mu \text{m} \) dust continuum map is convolved with the beam FWHM of NRO 45 m. The line widths of isolated components of \( \text{N}_{2}\text{H}^{+} \) 1–0 (\( F_{i} = 0 \), \( 1 \rightarrow 1 \), 2) of 1.72 and 2.67 km s\(^{-1}\) for G108–N and G108–S, respectively, are used. Calculated \( \text{N}_{2}\text{H}^{+} \) 1–0 column densities of G108–N and G108–S are \( 1.2 \times 10^{14} \)
Figure 13. Spectra of HCN 1–0 toward G108–N, G108–S1, G108–S2, G108–S3, and G108–S4 (top to bottom).

and $1.9 \times 10^{14}$ cm$^{-2}$, respectively. $T_{ex}$ from non-LTE calculation are 3.1 and 3.0 K for G108–N and G108–S, respectively, which are consistent with the result from the hyperfine structure (HFS) fitting method. However, the optical depths calculated using the non-LTE method are larger than those calculated by the HFS fitting. A fractional abundance of molecule $x$, $X(x)$, can be derived as

$$X(x) = N(x) / N(H_2)_{dust}.$$  \hfill (16)

The fractional abundances of $N_2H^+$ 1–0 are $1.2 \times 10^{-8}$ and $2.5 \times 10^{-8}$ for G108–N and G108–S, respectively. G108–N and G108–S have higher fractional abundances than previously studied dense cores ($X(N_2H^+) \sim 1 \times 10^{-10}$) by Caselli et al. (2002), Tafalla et al. (2002), and Di Francesco et al. (2004). On the other hand, the $N_2H^+$ 1–0 fractional abundances of two clumps are consistent with those of cores within “Clump-S” of PGCC G192.32–11.88 (Liu et al. 2016b), which are calculated under the assumption of LTE. The $T_{ex}$ of cores in “Clump-S” is about 5 K and the optical depths is about 4.

The fractional abundances of $N_2H^+$ 1–0 are listed in Table 6. For the non-LTE analysis of HCN 1–0, the 850 μm dust continuum map is convolved with the beam FWHM of KVN 21 m to derive the H$_2$ volume density. The HCN 1–0 spectra at the positions of the 850 μm emission peaks are presented in Figure 11. The line width of the strongest component of HCN 1–0 is used. We average the four values for G108–S1, S2, S3, and S4 as a representative value for G108–S for consistency with the $N_2H^+$ analysis. $T_{ex}$ from the non-LTE calculation for HCN 1–0 are 3.8 and 4.0 K toward G108–N and G108–S, respectively. The column densities of HCN 1–0 in G108–N and G108–S are $7.8 \times 10^{14}$ and $6.5 \times 10^{14}$ cm$^{-2}$, respectively. The optical depths from the non-LTE method are larger than those from the HFS analysis. The fractional abundances of HCN 1–0 are $3.9 \times 10^{-7}$ and $2.9 \times 10^{-7}$ for G108–N and G108–S, respectively. Derived parameters with HCN 1–0 are listed in Table 7.

5. Discussion

PGCC G108.84–00.81 is located close to dynamically active regions such as an H II region (Sh2-152) and an SNR (SNR G109.1–1.0). SNR G109.1–1.0 is located east of PGCC G108.84–00.81. A line profile composed of two components, a sharp single-peaked component with a broad component, was shown in the interacting regions between CO molecular clouds and SNRs (Seta et al. 1998; Su et al. 2014). Thus, the association between SNR G109.1–1.0 and the CO molecular cloud in the vicinity of the remnant has been previously investigated (Tatematsu et al. 1987, 1990). However, according to Tatematsu et al. (1990), any broad CO emission, which is possibly accelerated by SNR G109.1–1.0, was not detected.

The channel maps of the CO 1–0 line emission of PGCC G108.84–00.81 are shown in Figure 14. The CO emission distributes along two filaments. A thin filament to the east is seen from $-55$ to $-52$ km s$^{-1}$. The main filament, which includes G108–N and G108–S, is seen from $-52$ to $-46.5$ km s$^{-1}$. The two filaments may be interacting in the northeast region, where IRAS 22576+5843 is located.

| ID       | $T_{ex}$ (K) | $N(H_2)_{dust}$ ($\times 10^{14}$ cm$^{-2}$) | $\Delta v$ (km s$^{-1}$) | $N(N_2H^+)$ ($\times 10^{14}$ cm$^{-2}$) | $X(N_2H^+)$ ($\times 10^{-8}$) |
|----------|--------------|------------------------------------------|----------------|-------------------------------------|------------------|
| G108–N   | 13.4         | 9.9                                      | 1.72           | 1.2                                 | 2.5               |
| G108–S   | 12.5         | 7.8                                      | 2.67           | 1.9                                 | 2.5               |

| ID       | $T_{ex}$ (K) | $N(H_2)_{dust}$ ($\times 10^{14}$ cm$^{-2}$) | $\Delta v$ (km s$^{-1}$) | $N(HCN)$ ($\times 10^{14}$ cm$^{-2}$) | $X(HCN)$ ($\times 10^{-8}$) |
|----------|--------------|-------------------------------------------|----------------|--------------------------------------|------------------|
| G108–N   | 13.4         | 7.9                                       | 3.24           | 7.8                                  | 3.3               |
| G108–S   | 12.5         | 7.4                                       | 2.53           | 6.5                                  | 2.9               |
However, the broad CO emission, which would hint at this interaction, does not appear. The thin filament is located in front of the main filament and seems to form a shield against the SNR shocks. As mentioned in Section 3.2, CO 2–1/CO 1–0 ratios along the main filament are not enhanced by shocks. Therefore, the main filament seems unaffected by the SNR.

However, the star formation in G108–S seems affected by the southern H II region, Sh2-152; G180–S is probably bent due to external compression by Sh2-152 and the CO 2–1/CO 1–0 ratio is enhanced at the bent region (see Figure 5). The gravitational collapse and fragmentation of G108–S might be induced by Sh2-152. G108–S is more evolved than G108–N. G108–N is a massive prestellar clump while G108–S is fragmented into at least four cores, G108–S1, G108–S2, G108–S3, and G108–S4, and G108–S1 (IRS 1) and G108–S2 (IRS 2) are associated with Class I sources. The overall clump properties of G108–N and G108–S are similar, and their chemical status does not show any significant differences; G108–S is slightly more evolved than G108–N from the view of CO depletion.

By comparing the pressures of G108–S and Sh2-152, one can investigate whether the evolution of G108–S has been affected by Sh2-152. The internal pressure of Sh2-152 can be derived using (Morgan et al. 2004)

\[
P_{\text{HII}} \frac{k}{n} = 2n_e T_e.
\]

The effective electron temperature \( T_e \) is assumed to be 10^4 K. For the electron density, the peak value \( n_e = 2000 \text{ cm}^{-3} \) from Heydari-Malayeri & Testor (1981) is used. The derived \( P_{\text{HII}} /k \) is 4.0 x 10^7 cm^{-3} K. On the other hand, the molecular pressure inside G108–S is (Liu et al. 2012b)

\[
P_{\text{mol}} \frac{k}{n} = n T_{\text{eff}}.
\]

The \( P_{\text{mol}} /k \) is derived to be 7.3 x 10^5 cm^{-3} K with \( n = 4.5 \times 10^3 \text{ cm}^{-3} \) and \( T_{\text{eff}} = 83 \text{ K} \), which are obtained from the C^{18}O 2–1 emission. The pressure of Sh2-152 is two orders of magnitude larger than the internal pressure of G108–S. It suggests that G108–S could be compressed by Sh2-152 if the two are physically associated. More studies are needed to confirm whether the star formation in G108–S has indeed been induced by Sh2-152. In contrast, G108–N is quiescent and seems not yet affected by its surrounding environment.

Figure 14. Channel maps of CO 1–0 observed with PMO. Respective velocities are indicated in the upper left of each panel in km s\(^{-1}\). The grayscale levels are from 3 to 19 in steps of 2 K km s\(^{-1}\). The contours are from 3 to 19 in K km s\(^{-1}\).
The stability of G108–N was examined by comparing its total mass and the Jeans mass; the derived total mass is greater than the Jeans mass, indicating that G108–N is gravitationally unstable. The freefall time \( t_{ff} = 3.4 \times 10^7 \text{yr} \), Evans (1999) for G108–N is about 1 Myr, which is similar to the typical lifetime of low-mass starless cores with an average density of \( n \sim 10^4 \text{cm}^{-3} \). The lifetime for massive prestellar cores is expected to be shorter than the freefall time (André et al. 2014). Therefore, G108–N might be nearing collapse. However, it is unclear whether G108–N will survive as a single massive prestellar core or be fragmented into several components as seen for G108–S. The peak surface densities of G108–N and G108–S are similar to 0.07 g cm\(^{-2}\) as derived from the \(^{13}\text{CO} \ 1\to 0\) line. The value is much smaller than the threshold surface density (1 g cm\(^{-2}\), Krumholz & McKee 2008) for fragmentation in massive star formation. The estimated surface densities of IRDCs are 0.2–5 g cm\(^{-2}\) (Battersby et al. 2011). However, Urquhart et al. (2014) argued that adding the effect of an magnetic field could reduce the threshold of surface density for fragmentation. In addition, the distribution of surface densities of massive star-forming clumps shows that clumps a surface density lower than 0.1 g cm\(^{-2}\) can result in high-mass star formation (Figure 12 of Urquhart et al. 2014). Therefore, we cannot exclude the possibility that G108–N could form a high-mass star without fragmentation.

6. Summary

To investigate the star formation condition near active regions such as SNRs and H II regions, various molecular line observations, as well as submillimeter dust continuum observations toward PGCC G108.84–00.81 were carried out. Our results are as follows.

1. One filament structure presented in the integrated intensity maps of CO 1–0 and \(^{13}\text{CO} \ 1\to 0\) is largely divided into three parts: the northeast region associated with a star, IRAS 22576+5843, the southern region directly linked to a H II region, Sh2-152, and the central part defined here as G108, containing IRAS 22565+5839. The two clumps, “G108–N” and “G108–S,” are found within G108.

2. In G108–S, a blueshifted component whose velocity is similar to that of the component associated with Sh2-152 is shown in both of the Moment 1 maps of CO 2–1 and \(^{13}\text{CO} \ 2\to 1\). The integrated intensity ratio, \(^{13}\text{CO} \ 2\to 1/\text{CO} \ 1\to 0\), is also the most enhanced at the southern edge of G108–S, which is close to the H II region.

3. Dust continuum emission also shows two components corresponding to G108–N and G108–S. Highly fragmented structures in G108–S are revealed with the beam FWHM of JCMT/SCUBA-2 (\( \sim 14^\prime\)). Four components, G108–S1, G108–S2, G108–S3, and G108–S4, are identified in the G108–S region. G108–S1 has no associated IR source, while there are two IR sources corresponding with the dust continuum emission peaks, G108–S1 and G108–S2. The integrated intensity peaks of CO 2–1, \(^{13}\text{CO} \ 2\to 1\), and \(^{13}\text{CO} \ 1\to 0\) are slightly off that of dust continuum.

4. The HCO\(^+\) 1–0 and HCN 1–0 show similar distributions to each other and also similar to the distribution of 850 \( \mu \)m continuum emission in G108–N. The emission of two lines is distributed along the NE–SW direction with a cometary structure, while HCO\(^+\) 4–3 is shown only in the head part. This cometary structure is also shown in the integrated intensity map of \( \text{NH}_2 \) (1, 1). The centroid velocities of all lines are consistent.

5. IR sources, IRS 1 and IRS 2, associated with G108–S1 and G108–S2, respectively, are YSO candidates. IRS 1 and IRS 2 are classified as Class I sources. However, outflows associated with these Class I sources were not detected with our CO observations. Higher resolutions and better sensitivities might reveal associated outflows.

6. The \( T_{ex} \) derived from CO observations of G108–N and G108–S are 13.4 and 12.5 K, respectively. The total mass of G108–N is larger than the sum of total masses of G108–S1 to S4. The total mass of G108–N is larger than the Jeans mass, suggesting that G108–N is a prestellar clump, which is gravitationally unstable and thus a potential future star formation site.

7. Two clumps have similar properties, such as the gas temperature and the \( H_2 \) column density. Their chemical status does not show any significant differences, although G108–N is slightly less evolved than G108–S from the view of CO depletion.

8. The gravitational fragmentation and star formation in G108–S seem to be induced by the compression from the H II, Sh2-152; G108–S is bent toward Sh2-152 and the CO 2–1/\(^{13}\text{CO} \ 1\to 0\) ratio is enhanced at the bent region. In contrast, G108–N does not seem to be affected by its environment yet.

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