MOLECULAR CLOUDS IN THE NORTH AMERICAN AND PELICAN NEBULAE: STRUCTURES

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ABSTRACT
We present observations of a 4.25 deg² area toward the North American and Pelican Nebulæ in the \( J = 1-0 \) transitions of \(^{12}\)CO, \(^{13}\)CO, and \(^{18}\)O. Three molecules show different emission areas with their own distinct structures. These different density tracers reveal several dense clouds with a surface density of over 500 \( M_\odot \) pc\(^{-2} \) and a mean \( H_2 \) column density of 5.8, 3.4, and 11.9 \( \times 10^{21} \) cm\(^{-2} \) for \(^{12}\)CO, \(^{13}\)CO, and \(^{18}\)O, respectively. We obtain a total mass of 5.4 \( \times 10^4 \) \( M_\odot \) \(^{12}\)CO), 2.0 \( \times 10^4 \) \( M_\odot \) \(^{13}\)CO), and 6.1 \( \times 10^3 \) \( M_\odot \) \(^{18}\)O) in the complex. The distribution of excitation temperature shows two phases of gas: cold gas (~10 K) spreads across the whole cloud; warm gas (>20 K) outlines the edge of the cloud heated by the W80 \( H\) II region. The kinetic structure of the cloud indicates an expanding shell surrounding the ionized gas produced by the \( H\) II region. There are six discernible regions in the cloud: the Gulf of Mexico, Caribbean Islands and Sea, and Pelican’s Beak, Hat, and Neck. The areas of \(^{13}\)CO emission range within 2–10 pc\(^2 \) with mass of (1–5) \( \times 10^4 \) \( M_\odot \) and line width of a few km s\(^{-1} \). The different line properties and signs of star-forming activity indicate they are in different evolutionary stages. Four filamentary structures with complicated velocity features are detected along the dark lane in LDN 935. Furthermore, a total of 611 molecular clumps within the \(^{13}\)CO tracing cloud are identified using the ClumpFind algorithm. The properties of the clumps suggest that most of the clumps are gravitationally bound and at an early stage of evolution with cold and dense molecular gas.

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

Online-only material: color figures, machine-readable and VO tables

1. INTRODUCTION
The study of massive star formation is limited. The molecular clouds within a few hundred parsecs of the Sun provide an ideal environment for improving our knowledge of star-forming processes. Among these clouds, low-mass star-forming regions constitute the majority of the population, while regions with massive clumps and dense clusters like the Orion nebula are infrequent. The North American (NGC 7000) and Pelican (IC 5070) Nebulæ (referred to as the “NAN complex” hereafter) are together one of the nearby (~600 pc, Laugalys & Straizys 2002) star-forming regions with large numbers of massive stars. This is the next closest region showing signs of massive star formation after Orion, but has been rarely studied to date.

Studies of molecules (Bally & Scoville 1980; Dobashi et al. 1994) and near-infrared extinction (Cambresy et al. 2002) all confirm substantial quantities of molecular gas along the Lynds Dark Nebula (LDN) 935 (Lynds 1962), which lies between the North American and Pelican Nebulæ. All three objects (NGC 7000, IC 5070, and LDN 935) are thought to be a part of W80, a large \( H\) II region mainly in the background. Comerón & Pasquali (2005) identified an O5V star, 2MASS J205551.25+435224.6, hidden behind the LDN 935 cloud as the ionizing star of the \( H\) II region. Mid-infrared observations such as those from Midcourse Space Experiment (Egan et al. 1998) have found several infrared dark clouds in LDN 935, which indicates the existence of a cold, dense environment in the molecular cloud. Other signposts of ongoing star formation, such as HH objects and Ha emission-line stars (e.g., Bally & Reipurth 2003; Comerón & Pasquali 2005; Armond et al. 2011, etc.), are also found in the NAN complex. However, studies of molecules in the NAN complex, which can reveal both the spatial and velocity structures, have only been conducted in a few small regions or are limited by resolution.

In this work, we use molecular data tracing different environments to study the properties of the individual regions, filamentary structures, and clumps in the NAN complex. There is a divergence in the distance estimation of the complex as discussed by Wendker et al. (1983), Straizys et al. (1993), Cersosimo et al. (2007), etc., and reviewed by Reipurth & Schneider (2008). In our calculation, we adopt a commonly used distance of 600 pc based on multi-color photometric results for hundreds of stars (Laugalys & Straizys 2002; Laugalys et al. 2007).

2. OBSERVATIONS AND DATA REDUCTION
We observed the NAN complex in \(^{12}\)CO (1–0), \(^{13}\)CO (1–0), and \(^{18}\)O (1–0) with the Purple Mountain Observatory Delingha (PMODLH) 13.7 m telescope as one of the scientific demonstration regions for the Milky Way Imaging Scroll Painting project3 from 2011 May 27 to June 3. The three CO lines were observed simultaneously with the nine-beam superconducting array receiver (working in sideband separation mode and with the fast Fourier transform spectrometer employed (Shan et al. 2012). The typical receiver noise temperature \((T_{\text{rx}})\) is about 30 K as given by the status report4 of PMODLH.

Our observations were made in 17 cells of dimension 300 × 300' and covered a total area of 4.25 deg² (466 pc² at the distance of 600 pc) as shown in Figure 1. The cells were mapped using the on-the-fly (OTF) observation mode, with the standard chopper wheel method for calibration (Penzias & Burrus 1973). In this mode, the telescope beam is scanned along lines in R.A. and decl. directions on the sky at a constant rate of 50′ s\(^{-1} \), and the receiver records spectra every 0.3 s. Each cell was scanned in both R.A. and decl. direction to reduce the fluctuation of noise.

3 http://www.radioast.nsc.cn/yhhjindex.php
4 http://www.radioast.nsc.cn/zhuangtaibaogao.php
File perpendicular to the scanning direction. Further observations were made toward the regions with \textsubscript{C\textsubscript{18}O} detection to improve the signal-to-noise ratios. The typical system temperature during observations was $\sim 280$ K for \textsuperscript{12}CO and $\sim 185$ K for \textsuperscript{13}CO and \textsuperscript{C\textsubscript{18}O}.

After removing the bad channels in the spectra, we calibrated the antenna temperature ($T_a$) to the main-beam temperature ($T_{mb}$) with a main-beam efficiency of 44\% for \textsuperscript{12}CO and 48\% for \textsuperscript{13}CO and \textsuperscript{C\textsubscript{18}O}. The calibrated OTF data were then gridded to 30\" pixels and mosaicicked to a FITS cube using the GILDAS software package (Guilloteau & Lucas 2000). A first-order baseline was applied for the spectra. The resulting rms noise is 0.46 K for \textsuperscript{12}CO at the resolution of 0.16 km s$^{-1}$, 0.31 K for \textsuperscript{13}CO, and 0.22 K for \textsuperscript{C\textsubscript{18}O} at 0.17 km s$^{-1}$. Such a noise level corresponds to a typical integration time of $\sim 30$ s in each resolution element. A summary of the observation parameters is provided in Table 1.

3. RESULT

3.1. General Distribution of the Molecular Cloud

Figures 2–5 show the distributions of \textsuperscript{12}CO, \textsuperscript{13}CO, and \textsuperscript{C\textsubscript{18}O} emissions. The distributions are elongated in the southeast–northwest direction along the dark lane. \textsuperscript{12}CO presents bright, complex, extended emission throughout the mosaic, while \textsuperscript{13}CO presents several condensations, and \textsuperscript{C\textsubscript{18}O} only appears at those brightest parts. From the distribution of molecules, we distinguish by eye six regions and designated their names following Rebull et al. (2011). Positions of these regions are indicated on the composed image in Figure 2. The brightest portions in all three lines are the Gulf of Mexico (GoM) to the southeast and the Pelican to the northwest. Between these, there are filamentary structures (the Caribbean Islands) and an extended feature to the south (the Caribbean Sea) with a few pixels of \textsuperscript{C\textsubscript{18}O} detection. The Caribbean Islands and Sea regions are spatially coincident along the line of sight but are separate in the velocity dimension.

The channel map in Figure 6 illustrates the velocity structure of the molecules in the NAN complex. Three \textsuperscript{13}CO filaments are clearly presented in the velocity ranges of $-7$ to $-4$, $-3$ to $-2$, and $-1$ to 0 km s$^{-1}$. The latter two filaments connect the GoM and the Pelican’s Hat regions. The emissions in the GoM indicate an arc feature from 0 to 2 km s$^{-1}$. Along with the Caribbean Sea, they show complicated structures in the following positive velocity panels. There is another filamentary structure near the Pe\’lican’s Beak, in the velocity range 3–4 km s$^{-1}$.

The velocity-coded image shown in Figure 7 indicates the velocity distribution of the emission peak of \textsuperscript{13}CO. Near the center of the whole complex, there are several velocity components with high peak separation, and three filamentary structures showing with different colors overlapping each other. The velocity components of the Pelican region in the northwest are relatively simple, while the peak velocities in the southeast show a component around 0 km s$^{-1}$, which outlines the GoM region, and another separated extended component at 3–4 km s$^{-1}$. Such a velocity structure could also be seen on the position–velocity map in Figure 8 along the axis through the full length of the complex in Figure 7. In the center region of the whole complex, the molecular emission near $-1$ km s$^{-1}$ is lacking and forms a cavity structure. Bally & Scoville (1980) pointed out that the molecular gas in the northwest part of the

| Line | $\nu_0$ (GHz) | HPBW (\") | $T_{sys}$ (K) | $\eta_{mb}$ | $\delta v$ (km s$^{-1}$) | $T_{mb}$ rms noise (K) |
|------|--------------|------------|---------------|-------------|------------------------|-----------------------|
| \textsuperscript{12}CO | 115.271204 | 52 ± 3 | 220–500 | 43.6\% | 0.160 | 0.46 |
| \textsuperscript{13}CO | 110.201353 | 52 ± 3 | 150–310 | 48.0\% | 0.168 | 0.31 |
| \textsuperscript{C\textsubscript{18}O} | 109.782183 | 52 ± 3 | 150–310 | 48.0\% | 0.168 | 0.22 |

Notes. The columns show the line observed, rest frequency of the line, half-power beam width of the telescope, system temperature, main-beam efficiency, velocity resolution, and rms noise of the main-beam temperature. The beam width and main-beam efficiency are given by the status report of the telescope.

Figure 1. Location of observation coverage, superimposed on the second Palomar Observatory Sky Survey (POSS II) red image. Green crosses mark the T-Tauri-type stars identified by Herbig (1958).

Figure 2. Composite color image of the NAN complex made from the integrated intensity map, with \textsuperscript{12}CO in blue, \textsuperscript{13}CO in green, and \textsuperscript{C\textsubscript{18}O} in red, respectively. The spectra are integrated over $-20$ to 20 km s$^{-1}$ for \textsuperscript{12}CO and \textsuperscript{13}CO, and $-10$ to 10 km s$^{-1}$ for \textsuperscript{C\textsubscript{18}O}. We also overlay outlines of the six regions with their names on the plot.

Table 1

| Line | $\nu_0$ (GHz) | HPBW (\") | $T_{sys}$ (K) | $\eta_{mb}$ | $\delta v$ (km s$^{-1}$) | $T_{mb}$ rms noise (K) |
|------|--------------|------------|---------------|-------------|------------------------|-----------------------|
| \textsuperscript{12}CO | 115.271204 | 52 ± 3 | 220–500 | 43.6\% | 0.160 | 0.46 |
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| \textsuperscript{C\textsubscript{18}O} | 109.782183 | 52 ± 3 | 150–310 | 48.0\% | 0.168 | 0.22 |
Nan complex belongs to an expanding shell surrounding the ionized gas produced by the W80 H II region.

In Figure 9, we illustrate the kinematics of the molecular shell near the Pelican region in detail. We could derive an expansion velocity of $\sim 5$ km s$^{-1}$. The Pelican’s Hat at the far end is $\sim 14$ pc away from the center of the H II region. The cloud near the ionizing star at $\sim 0$ km s$^{-1}$ connects to the GoM region. Its velocity is close to the rest velocity of the whole complex, which is probably because the molecular gas in this region has not been penetrated by the shock of the H II region (Bally & Scoville 1980). In Figure 8, we further find that there is a velocity gradient of $\sim 0.2$ km s$^{-1}$ pc$^{-1}$ within the complex along the axis of the position–velocity map.

Our mapping region contains total areas of 403 pc$^2$ with $^{12}$CO detection, 225 pc$^2$ with $^{13}$CO detection, and 18 pc$^2$ with C$^{18}$O detection over 3$\sigma$ at the distance of 600 pc. Under the assumption of local thermodynamic equilibrium (LTE), we derive the excitation temperature from the radiation temperature of $^{12}$CO. The distribution of excitation temperature shown in Figure 10 indicates gases of two different temperatures within the Nan complex: localized warm gas ($> 20$ K) in the Caribbean Islands, in Pelican’s Neck and Beak, and in some small clouds to the southeast; and extended cold gas ($< 10$ K) distributed throughout the whole of the dark nebula. The warm gas clearly matches the edge of the whole cloud, suggesting that the warm clouds are heated by the background H II regions.

We further calculate the column density and LTE mass with the $^{13}$CO data following the process given by Nagahama et al. (1998) and adopting a $^{13}$CO abundance of $N(H_2)/N(^{13}$CO) $= 7 \times 10^8$. We obtain a total mass of $2.0 \times 10^4 M_\odot$ in the Nan complex. Using the abundance of $N(H_2)/N(C^{18}$O) $= 7 \times 10^6$ (Castets & Langer 1995), an LTE mass based on C$^{18}$O data can also be derived as $6.1 \times 10^3 M_\odot$. If we simply use the CO-to-H$_2$ mass conversion factor $\chi$ of $1.8 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ given in the CO survey of Dame et al. (2001), a mass of $5.4 \times 10^4 M_\odot$ can be derived for the complex. The mass of inner denser gas traced by $^{13}$CO accounts for 36% of the mass in a larger area traced by $^{12}$CO, while the mass in a few small dense clouds traced by C$^{18}$O accounts for 11% of the total mass.

In our calculation, we obtained a mean H$_2$ column density of $5.8 \times 10^{13}$ cm$^{-2}$ based on $^{12}$CO emission by averaging all pixels with line detection. A similar method produces a mean column density of $3.4 \times 10^{21}$ cm$^{-2}$ traced by $^{13}$CO and C$^{18}$O, respectively. We show the surface density map for the three molecular species in Figure 11. All three tracers show a maximum surface density over $500 M_\odot$ pc$^{-2}$ in the Pelican’s Neck region, while the GoM region is optically thick with high surface density only in the C$^{18}$O map. The 3$\sigma$ noise at $T_{\text{sys}} = 10$ K within a velocity width of 40 km s$^{-1}$ corresponds to 14, 19, and 146 $M_\odot$ pc$^{-2}$ in the $^{12}$CO, $^{13}$CO, and C$^{18}$O maps, respectively. Therefore, the mass hidden under our detection limit of $^{13}$CO is lower than $5.4 \times 10^2 M_\odot$, which indicates that the discrepancy in the obtained mass between $^{12}$CO and $^{13}$CO is mainly the result of the different emission area tracing by them.
The hidden mass for C$^{18}$O is $1.4 \times 10^3 M_\odot$ at most, significantly lower than the total mass traced by $^{13}$CO. This means that we have detected over 80% of mass in our C$^{18}$O observation area.

Bally & Scoville (1980) observed a similar field in the NAN complex and estimated the LTE mass as $(3-6) \times 10^4 M_\odot$ for a
distance of 1 kpc and $^{13}$CO abundance of $N(\text{H}_2)/N(^{13}\text{CO}) = 1 \times 10^6$. For the same parameters as we used, it would correspond to $(1-2) \times 10^4 M_\odot$. Cambrèsy et al. (2002) obtained a mass of $4.5 \times 10^4 M_\odot$ for a distance of 580 pc in their near-infrared extinction study covering an area of 6.25 deg$^2$ in the NAN complex. These discrepancies of mass might be due to the dust-to-gas ratio or the $X$ factor.

### 3.2. Features in Individual Regions

Several discernible regions and filamentary structures can be identified in our observations. The spectra observed toward the regions are shown in Figure 12. The variety of line profile and intensity ratios indicates distinct kinematic and chemistry environments. Their properties probed by different tracers are summarized in Table 2, and details for each region are listed below.

The “Gulf of Mexico” is the largest and the most massive region, with all three line detections in the southeast of the NAN complex. Two major clumps can be found in this region: one in the north (GoM N) with weak C$^{18}$O emission, and one in the south (GoM S) with strong C$^{18}$O emission, indicating a pair of parallel arcs, which closely matches the morphology of the filamentary dark cloud in Spitzer mid-infrared images (Guieu et al. 2009; Rebull et al. 2011). The $^{12}$CO spectra are flat-topped, indicating high opacity at these locations. Under the LTE assumption, we find a low excitation temperature ($\sim 14$ K), large line width, and weak C$^{18}$O emission. The molecular emission shows a bright feature oriented in the north–south direction, with a sharp cutoff toward the east. Several IRAS sources are associated with the peaks on the $^{13}$CO map. A position–velocity slice along the east edge of the Pelican’s Neck (as in Figure 14) reveals a weak component at $\sim 3$ km s$^{-1}$ that is separate from the molecular clump and forms a cavity near IRAS 20489+4410 and IRAS 20490+4413 in the velocity dimension. Such a structure could be the result of an embedded H ii region.

The molecular emission in Pelican’s Neck matches the morphology of the brightest surface brightness region in Spitzer mid-infrared images, and it is at the west edge of the Pelican Cluster, an active star-forming cluster of YSOs identified by Rebull et al. (2011). A clustering of T-Tauri-type stars (Herbig 1958) was found around the molecular clump. These all indicate that the Pelican’s Neck is a warm region with active star formation.

The “Pelican’s Beak” region is a small elongated region to the southeast of Pelican’s Neck. The excitation temperature is intermediate ($\sim 15$ K) with weak C$^{18}$O emission. The molecules protrude along a filament to the south at the velocity of 3 km s$^{-1}$. Its properties may suggest an intermediate stage
Islands are part of a filamentary structure (see Section 3.3). The Caribbean Sea is a diffuse extended cloud to the west of GoM and to the east of Pelican’s head. The channel map indicates that these southern half of the Caribbean Islands is spatially coincident from the west of GoM and to the east of Pelican’s head. The Islands). blobs in Spitzer (see Section 3.3). They associate with several highly localized nebulous bright regions (e.g., Pelican’s Neck, Caribbean Islands) between the cold dense regions (e.g., GoM, Pelican’s Hat) and the warm active regions (e.g., Pelican’s Neck, Caribbean Islands). The “Caribbean Islands” are several bright clumps extending from the west of GoM and to the east of Pelican’s head. The southern half of the Caribbean Islands is spatially coincident with the Caribbean Sea. The channel map indicates that these “Islands” are part of a filamentary structure (see Section 3.3). They associate with several highly localized nebulous bright blobs in Spitzer mid-infrared images (Rebull et al. 2011). These clumps show a high excitation temperature, narrow line width, and low relative abundance of C18O. These properties indicate a similar situation to that in Pelican’s Neck. Together with Pelican’s Neck, the north part of the Caribbean Islands forms a cavity structure at the position of the Pelican Cluster that can be seen on the 13CO integrated intensity map.

The molecular cloud in the northernmost part of this region is associated with an H II region, G085.051−0.182 at −0.2 km s$^{-1}$, identified by Lockman et al. (1996). Figure 15 shows that the H II region is not associated with any dense molecular clumps at its rest velocity. Dense and heated gas with temperature ~27 K appears within the velocity from ~6 to ~3 km s$^{-1}$ near the position of the H II region, while diffuse clumps are shown in the panels with positive velocities. The position–velocity map shows an incomplete asymmetric molecular shell around the H II region. It is notable that the densest part of the heated clumps tracing by C18O presents a slightly higher velocity, which is closer to the rest velocity of the H II region than those tracing by 12CO and 13CO. These indicate that the H II region undergoes an asymmetric expansion within the parent molecular cloud.

The “Caribbean Sea” is a diffuse extended cloud to the west of GoM at the velocity of 3 km s$^{-1}$ with low excitation temperature and optical depth. 12CO is detected in a large area, and weak C18O emission can only be detected at a few positions. This region shows the lowest column density among all the regions, but its total mass is relatively high.

### 3.3. Filamentary Structures

In our observations with velocity dimensions, we resolve three separate filamentary structures (designated as F-1, F-2, F-3 in ascending velocity order) nearly parallel to each other along the dark lane in the NAN complex. Another filament (F-4) is also resolved near the Pelican’s Beak region. Figure 7 shows the positions of the filaments, with different colors representing their different velocities. Figures 16 and 17 show the morphology and velocity structure of these filaments. We found elongated molecular clumps along these filaments. F-1, which contains the bright clumps in the Caribbean Islands, presents a complex twisted spatial and velocity structure, with a ring-like structure near 20$^5$54$^m$.5, +44$^\circ$19$'$.

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**Table 2** Properties of Regions

| Region            | $T_{ex}$ (K) | Area (pc$^2$) | $N_{H_2}$ (10$^{22}$ cm$^{-2}$) | $M$ (10$^5$ $M_\odot$) | Area (pc$^2$) | $N_{H_2}$ (10$^{22}$ cm$^{-2}$) | $M$ (10$^5$ $M_\odot$) | $\Delta v$ (km s$^{-1}$) | Area (pc$^2$) | $N_{H_2}$ (10$^{22}$ cm$^{-2}$) | $M$ (10$^5$ $M_\odot$) | \(\frac{N(C^{18}O)}{N(13CO)}\) |
|-------------------|--------------|---------------|---------------------------------|-------------------------|---------------|---------------------------------|-------------------------|-------------------------|---------------|---------------------------------|-------------------------|-------------------------|
| Gulf of Mexico    | 14.2         | 18.2          | 1.2                             | 11.8                    | 5.7           | 1.3                             | 5.4                     | 5.93                    | 2.0           | 2.5                             | 32.0                     | 0.13                    |
| Pelican’s Hat     | 12.2         | 16.4          | 0.7                             | 4.1                     | 4.6           | 0.6                             | 1.7                     | 4.37                    | 1.3           | 1.3                             | 8.4                      | 0.14                    |
| Pelican’s Neck    | 22.8         | 4.4           | 1.6                             | 6.0                     | 3.4           | 1.6                             | 3.1                     | 2.99                    | 0.6           | 2.4                             | 9.9                      | 0.07                    |
| Pelican’s Peak    | 15.9         | 7.5           | 1.1                             | 4.8                     | 2.2           | 0.8                             | 1.3                     | 2.24                    | 0.3           | 1.1                             | 1.3                      | 0.08                    |
| Caribbean Islands | 18.7         | 19.2          | 1.3                             | 12.3                    | 2.2           | 1.3                             | 5.0                     | 2.98                    | 0.3           | 3.6                             | 8.5                      | 0.11                    |
| Caribbean Sea     | 12.1         | 41.6          | 0.7                             | 8.1                     | 10.2          | 0.4                             | 2.5                     | 3.86                    | ...           | ...                             | ...                      | ...                     |

**Notes.** The properties of the regions in the NAN complex, including excitation temperature, area within the half-maximum contour line, mean column density of H$_2$, mass of 12CO, 13CO, and C18O, line width of averaged spectra for 13CO, and integrated intensity ratio of C18O to 13CO. The column density and mass for 13CO are derived with a constant CO-to-H$_2$ mass conversion factor, and those for 13CO and C18O are derived under the LTE assumption. The C18O properties in the Caribbean Sea are missing because of the low C18O detection rate in this region.
Figure 12. Typical spectra in the selected regions with names in the upper left corner. These spectra are averaged within a 2' × 2' box centered at the positions (R.A., decl.) marked at the lower right corner.

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

Figure 13. Integrated intensity ratio of C^{18}O to ^13CO. The two panels show the same region as that in Figure 5. Names of the regions are marked on the map.

(A color version of this figure is available in the online journal.)
The Astronomical Journal, 147:46 (16pp), 2014 March

Zhang, Xu, & Yang

Figure 14. Left: the $^{13}$CO integrated intensity map of Pelican’s Neck. Red stars indicate the position of IRAS point sources. The names of three massive sources are indicated. The blue arrow indicates the axis of the position–velocity map. Right: position–velocity map along the axis shown in the left panel. The grayscale background indicates $^{12}$CO, black contours indicate $^{13}$CO, and white contours indicate C$^{18}$O. The lowest contour is $10\sigma$ for $^{13}$CO and $10\sigma$ for C$^{18}$O. The vertical dashed line indicates the rest velocity averaged over the whole region. Projected positions of three IRAS sources are marked. (A color version of this figure is available in the online journal.)

Figure 15. Top: channel map of $^{13}$CO near the H\textsc{ii} region in the Caribbean Islands region. The cross in each panel marks the position of the H\textsc{ii} region, G085.051−0.182, reported by Lockman et al. (1996). The central velocity of each channel, in km s$^{-1}$, is marked on the top left corner of each map. The blue arrow is the axis of the position–velocity map. Bottom: position–velocity map along the axis shown in the top panel. The grayscale background indicates $^{12}$CO, black contours indicate $^{13}$CO, and white contours indicate C$^{18}$O. The lowest contour is $5\sigma$ for $^{13}$CO and $10\sigma$ for C$^{18}$O, with the contour interval of $5\sigma$. The cross indicates the rest velocity and the position of the H\textsc{ii} region. (A color version of this figure is available in the online journal.)

Table 3

| Filament | $T_{ex}$ (K) | $\Delta v$($^{13}$CO) (km s$^{-1}$) | $\tau$($^{13}$CO) | $M$ ($M_\odot$) | $M/l$ ($M_\odot$ pc$^{-1}$) |
|----------|-------------|----------------------------------|----------------|-------------|---------------------|
| F-1      | 16          | 3.20                             | 0.33           | 1401        | 107                |
| F-2      | 12          | 3.77                             | 0.34           | 416         | 30                 |
| F-3      | 12          | 3.52                             | 0.36           | 487         | 32                 |
| F-4      | 17          | 2.75                             | 0.26           | 196         | 38                 |

Notes. The properties of the filaments in the NAN complex, including excitation temperature, line width of averaged spectra, optical depth of $^{13}$CO, mass, and mass per unit length. These typical values are the results averaged within the $10\sigma$ contour line of each filament.

3.4. Clump Identification

We use the FINDCLUMPS tool in the CUPID package (a library of the Starlink package) to identify molecular clumps discontinuous, and, together with the Pelican’s Hat region, they form a hub-filament structure (Myers 2009). The northwest and southeast sections of F-2 show opposite velocity gradient directions. The northwest section of F-3 bends to the east with higher velocity and surrounds the Pelican Cluster. Both F-2 and F-4 show clear velocity gradients along their axes in the position–velocity map.

We show the averaged spectra in Figure 18, and some physical properties of the filaments are listed in Table 3. A typical $^{13}$CO line width of 3.3 km s$^{-1}$ is shown. These filamentary structures show similar optical depths, while F-1 and F-4 have a higher excitation temperature. We could estimate the mass per unit length by dividing the mass of filaments by their spatial dimension. F-1 shows a higher mass per unit length than that in the other filaments. The twisted structure in F-1 may cause an overestimation of this measurement. A maximum, critical linear mass density needed to stabilize a cylinder structure can be calculated with $(M/l)_{max}=84(\Delta v)^2M_\odot$ pc$^{-1}$ in the turbulent support case, where $\Delta v$ is the line width in units of km s$^{-1}$ (Jackson et al. 2010). This means our filaments are gravitationally stable on the assumption of the $^{13}$CO abundance we adopted.
Figure 16. $^{13}$CO moment maps of the filaments showing the integrated intensity (left), rest velocity (middle), and line width (right). In each panel, the zeroth-moment contour lines are overlaid from $7\sigma$ with $10\sigma$ intervals. The name and the velocity range of each filament are marked in the top left corner in each panel.

(A color version of this figure is available in the online journal.)
in the obtained $^{13}$CO FITS cube. The ClumpFind algorithm is applied in the process of identification. The algorithm first contours the data and searches for peaks to locate the clumps, and then it follows them down to lower intensities. We set the parameters $T_{\text{LOW}} = 5 \times \text{RMS}$ and $\Delta T = 3 \times \text{RMS}$, where $T_{\text{LOW}}$ determines the lowest level to contour a clump, and $\Delta T$ represents the gap between contour levels that determines the lowest level at which to resolve merged clumps (Williams et al. 1994). The parameters of each clump, such as the position, velocity, size in R.A. and decl. directions, and one-dimensional velocity dispersion, are directly obtained in this process. The clump size has removed the effect of beam width, and velocity dispersion is also de-convolved from the velocity resolution. The morphology of the clumps is checked by eye within the three-dimensional R.A.–decl.–velocity space to pick out clumps with meaningful structures. We then mark every clump on their velocity channel in the $^{13}$CO cube to confirm the morphology and emission intensity of the molecular gas within the clumps. In addition, clumps with pixels that touch the edge of the data cube are removed. Twenty-two clumps are removed in these checking steps. Eventually, a total of 611 clumps are identified, and the position, velocity, and size of the clumps as illustrated in Figure 19 are consistent with the spatial and velocity distribution of the molecular gas.

We extract the excitation temperature for each clump from their $^{12}$CO data cube under LTE assumption and can then derive the LTE mass. The parameters of the clumps are listed in Table 4. The clump size is derived from the geometric

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Figure 17. $^{13}$CO position–velocity map of the four filamentary structures along the axes shown in the integrated intensity maps of Figure 16. The lowest contour is $5\sigma$, and the contour interval is $5\sigma$ for each panel. Red dashed lines indicate the velocity range of each filament.

Figure 18. Position-averaged $^{13}$CO spectra of the filaments. Spectra are moved upward for clarity. The name of each filament is marked on the left of each spectrum.

Figure 19. Clumps identified in the $^{13}$CO data cube. The circles indicate the clump positions on the integrated intensity map of $^{13}$CO. The colors of the circles represent the velocities the clumps, while the circles are scaled according to the sizes of clumps.
mean of the clump size in two directions. Figure 20 shows the distributions of clump size, excitation temperature, and volume density, which yield typical properties of $\sim 0.3$ pc, 13 K, and $8 \times 10^3$ cm$^{-3}$, respectively. The left panel in Figure 21 shows the distribution of three-dimensional velocity dispersion estimated as $\sigma_{3D} = \sqrt{3}\sigma_{1D}$. The thermal portion in the velocity dispersion is $\sigma_{\text{Thermal}} = \sqrt{kT_{\text{Kin}}/m}$, where $k$ is the Boltzmann constant, $m$ is the mean molecular mass, and $T_{\text{Kin}}$ is the kinetic temperature equal to the excitation temperature, while the non-thermal portion is $\sigma_{\text{Non-thermal}} = \sqrt{\sigma_{1D}^2 - \sigma_{\text{Thermal}}^2}$. The distributions of the thermal and non-thermal velocity dispersions are shown in Figure 21. There are 568 (93%) clumps with $\sigma_{\text{Non-thermal}}$ larger than $\sigma_{\text{Thermal}}$. The mean ratio of $\sigma_{\text{Non-thermal}}$ to $\sigma_{\text{Thermal}}$ is 1.57. This suggests that non-thermal broadening mechanisms (e.g., rotation, turbulence) play a dominant role in the clumps.

![Figure 20](image1.png)

**Figure 20.** Distribution of clump size (left), excitation temperature (middle), and volume density (right). The size is the geometric mean of the size in the R.A. and decl. direction, and density is derived under the spherical assumption. The range and typical value of each property are marked on each plot.

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

![Figure 21](image2.png)

**Figure 21.** Histogram of three-dimensional velocity dispersion (left), and the thermal (middle) and non-thermal (right) one-dimensional velocity dispersions. The range and typical value of each velocity dispersion are marked on each panel.

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

### Table 4

| Clump | R.A. (J2000) | Decl. (J2000) | Velocity (km s$^{-1}$) | R.A. ($''$) | Decl. ($''$) | $\delta_{1D}$ (pc) | $T_{\text{peak}}$ (K) | $T_{\text{ex}}$ (K) | $\Sigma$ ($n_H$) (10$^3$ cm$^{-3}$) | $M_{\text{LTE}}$ ($M_\odot$) | $\alpha_{\text{Vir}}$ |
|-------|-------------|---------------|------------------------|------------|--------------|-----------------|-------------------|----------------|---------------------------------|------------------|-------------|
| 1     | 20 48 01.2  | +43 42 59.4   | +0.01                  | 115.9      | 120.7        | 0.17            | 0.35              | 4.40           | 16.67                           | 23.9             | 11.2        | 15.6          | 1.52 |
| 2     | 20 48 01.6  | +43 34 43.8   | +1.13                  | 139.2      | 178.4        | 0.23            | 0.35              | 4.57           | 17.73                           | 31.9             | 10.1        | 33.2          | 0.98 |
| 3     | 20 48 15.2  | +43 40 59.4   | +1.50                  | 128.9      | 160.3        | 0.21            | 0.24              | 3.62           | 15.32                           | 17.0             | 5.2         | 13.1          | 1.07 |
| 4     | 20 48 20.6  | +43 31 04.7   | +0.99                  | 56.5       | 94.2         | 0.10            | 0.28              | 3.27           | 14.66                           | 6.9              | 5.6         | 1.8           | 5.00 |
| 5     | 20 48 37.6  | +43 48 11.8   | +1.01                  | 194.6      | 319.4        | 0.36            | 0.56              | 3.73           | 18.72                           | 40.1             | 5.7         | 74.4          | 1.74 |
| 6     | 20 48 41.2  | +43 39 38.6   | +1.67                  | 52.0       | 31.2         | 0.06            | 0.21              | 7.21           | 14.41                           | 9.8              | 29.7        | 1.6           | 1.80 |
| 7     | 20 48 42.3  | +44 21 38.6   | -4.26                  | 47.5       | 65.4         | 0.08            | 0.36              | 5.19           | 17.79                           | 15.3             | 26.4        | 3.9           | 3.09 |
| 8     | 20 48 44.2  | +43 40 15.1   | +2.25                  | 32.2       | 79.2         | 0.07            | 0.19              | 6.69           | 13.16                           | 7.2              | 10.6        | 1.2           | 2.58 |
| 9     | 20 48 44.8  | +43 52 52.4   | +1.47                  | 169.5      | 193.1        | 0.26            | 0.27              | 3.61           | 16.00                           | 17.9             | 3.0         | 14.8          | 1.46 |
| 10    | 20 48 46.3  | +44 15 17.7   | +1.95                  | 45.3       | 80.5         | 0.09            | 0.40              | 6.49           | 24.47                           | 38.2             | 53.3        | 9.9           | 1.63 |

**Notes.** The properties of the clumps in the NAN complex. Columns are clump number, clump position (R.A. and decl.), rest velocity, clump radius, one-dimensional velocity dispersion, temperature of emission peak, excitation temperature, surface density, volume density, LTE mass, and virial parameter.

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)
4. DISCUSSION

4.1. Comparison with Other Star Formation Regions

In a typical low-mass star-forming region, the Taurus region, Goldsmith et al. (2008) gives an LTE column density of \(<10^{22} \text{ cm}^{-2}\) for the most dense region based on the data from the Five College Radio Astronomy Observatory survey (Narayanan et al. 2008). This column density is lower than the averaged column density we derived in several dense regions of the NAN complex. Qian et al. (2012) searched for clumps in the Taurus survey data and derived a typical mean \(H_2\) density of \(\sim2000 \text{ cm}^{-3}\), lower than the clump density in the NAN complex of 8000 \(\text{ cm}^{-3}\). In addition, we found a number of clumps with densities over \(10^5 \text{ cm}^{-3}\), which is hardly seen in the Taurus region. The \(^{13}\text{CO}\) line width (0.4–2.2 km s\(^{-1}\)) in the NAN complex is also slightly higher than that in Taurus (0.5–1.7 km s\(^{-1}\)). These may indicate that potential massive stars are forming in some of the dense clumps in the NAN complex.

In an active high-mass star-forming region, such as the Orion Nebula, a survey of the Orion A region by Nagahama et al. (1998) yielded an averaged column density similar to our results. Their survey found regions with excitation temperature \(\geq20\ \text{ K}\) in most areas, and an even higher temperature of \(\geq60\ \text{ K}\) in the Orion KL region. Meanwhile, the high-temperature regions in the NAN complex are limited to those around the Pelican Cluster. In fact, the statistical properties of the clumps we identified in the NAN complex are similar to those of the Planck cold dense core (Planck Collaboration et al. 2011) of the Orion complex as studied by Liu et al. (2012). These results suggest that most of the clumps, especially the cold ones, in the NAN complex are in an early evolutionary stage of star formation dominated by a non-thermal environment.

4.2. Gravitational Stability of the Clumps

The gravitational stability of clumps determines whether the molecular clump could further collapse and form a star cluster. We first calculate the escape velocity \(v_{\text{escape}} = \sqrt{2GM_{\text{LTE}}/R}\) for each clump and compare with its three-dimensional velocity dispersion. The escape velocities range from 0.21 to 2.84 km s\(^{-1}\) with a typical value of 0.64 km s\(^{-1}\). About 493 (72\%) clumps have velocity dispersion smaller than escape velocity, and only 8 (1\%) clumps have velocity dispersion larger than twice the escape velocity. We note that the clumps with high \(\sigma_{3D}/v_{\text{escape}}\) ratios are faint with low emission peaks.

By simply assuming that the clumps have a density profile of \(\rho(r) = r^{-k}\) with power-law index \(k = 1\), we could further derive the virial mass using the standard equation (e.g., Solomon et al. 1987; Evans 1999; \(M_{\text{Vir}} = 1.164R\sigma_{1D}^2[M_\odot]\), where the clump size \(R\) is in pc, and three-dimensional velocity dispersion \(\sigma_{1D}\) is in km s\(^{-1}\). A steeper power-law index of \(k\) would result in a lower estimation of virial mass. The virial parameter, defined as the ratio of virial mass to LTE mass (\(\alpha_{\text{vir}} = M_{\text{Vir}}/M_{\text{LTE}}\)), describes the competition of internal supporting energy against the gravitational energy. We find a typical virial parameter of 2.5 in our clump sample. The virial masses are comparable to the LTE masses. There are 588 (96\%) clumps with virial mass larger than LTE mass, and 221 (36\%) clumps with virial parameter larger than 3. The clumps with high virial parameter (\(\alpha_{\text{vir}} > 10\)) are all faint ones with emission peak lower than 3.3 K. The clumps with \(\alpha_{\text{vir}} < 1\) are virialized and could be collapsing, while the clumps with higher \(\alpha_{\text{vir}}\) could be in a stable or expanding state unless they are external pressure confined.

4.3. Larson Relationship and Mass Function of Clumps

Larson (1981) presents a correlation between the velocity dispersion and the region size (range from 0.1 to 100 pc),
Figure 23. Left: virial mass–LTE mass relation of the clumps. Right: Jeans mass–LTE mass relation of the clumps. The dot–dashed green line indicates a mass ratio of 1. The solid red line shows a power-law fit to the relationship. The dashed blue line in the left panel indicates the median mass ratio.

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

Figure 24. Larson relationship for the clumps. The red line indicates a linear fitting to the clump size and velocity dispersion relation.

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

Figure 25. Clump mass function (CMF) for the clumps. The red dashed line fits the power-law distribution from 15 to 300 $M_\odot$.

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

known as the Larson relationship. The Larson relationship was suggested to exist by several works (Leung et al. 1982; Myers et al. 1983), but some recent molecular surveys suggest weak or no correlation between line width and size of molecular clouds (Onishi et al. 2002; Liu et al. 2012). Figure 24 shows the relationship between size and three-dimensional velocity dispersion for our clumps. A fitting to the data gives a correlation of $\sigma_{3D}/(\text{km s}^{-1}) = (1.00 \pm 0.03) \times \text{[Size/(pc)]}^{0.43 \pm 0.02}$, with a correlation coefficient of 0.63. The power-law index is slightly larger than 0.39 given by Larson (1981). The correlation is not strong, which might be the result of small dynamic range, and of the scattering of velocity dispersion and clump size (0.06–1.26 pc) we found. The dynamic range is limited by the sensitivity of observations. A uniform survey with sufficient high sensitivity will improve the completeness of less intense clumps with low column density and small size. On the other hand, Liu et al. (2012) pointed out that turbulence plays a dominant role in shaping the clump structures and density distribution at a large scale, while the small-scale clumps are easily affected by the fluctuations of density and temperature. This will cause a large scattering of line width broadening induced by other factors other than turbulence at small scales.

Such scattering of the velocity dispersion may result in a weak or even absent relationship.

We then study the clump mass function (CMF) in Figure 25 based on the clump mass sample we derived. A power-law distribution of $dN/d \log M \propto M^{-\gamma}$ is fitted with our data. Our power-law index (0.95) is lower than the stellar initial mass function (IMF) of 1.35 given by Salpeter (1955). Several (sub)millimeter continuum studies (Testi & Sargent 1998; Johnstone & Bally 2006; Reid & Wilson 2006) and molecular observations (Ikeda & Kitamura 2009) obtained CMFs that are consistent with the Salpeter IMF, while Kramer et al. (1998) reported a flatter power-law index of 0.6–0.8 in their CO isotope study of seven molecular clouds. The similarity between CMF and IMF power-law indices could simply be explained by a constant star formation efficiency unrelated to the mass and self-similar cloud structure, based on a scenario of one-to-one transformation from cores to stars (Lada et al. 2008). However, such a scenario is oversimplified and ignores the fragmentation in cores whose masses exceed the Jeans mass. Fragmentation in prestellar cores has been observed and discussed by several works (Goodwin et al. 2007; Chen & Arce 2010; Maury et al. 2010). In addition, a simulation by Swift & Williams (2008) suggested that the
obtained IMF is similar to the input CMF even when different fragmentation modes are considered.

4.4. YSOs in Molecular Clouds

Cambrésy et al. (2002) identified nine young stellar clusters in the NAN complex, and Guieu et al. (2009) provided a list of more than 1600 YSOs in their four Infrared Array Camera band study with the Spitzer Space Telescope. Lately, Rebull et al. (2011) incorporated their Multiband Imaging Photometer for Spitzer observations with earlier archival data and identified a list of 1286 YSOs in the NAN complex. We compare the distribution of the YSOs from Rebull et al. (2011) with our molecular observations in Figure 26. The Class I and flat sources are concentrated in cold and dense molecular clouds, especially in the GoM and the Pelican’s Hat region, while the Class II sources are spread across the cloud with low molecular opacity, and only a few YSOs are associated with the diffuse Caribbean Sea region. The molecular properties associated with different classes of YSOs are extracted and studied in Figure 27. The histograms indicate that the Class I and flat sources match the distribution of molecular clouds and prefer a cold dense environment with excitation temperature of \( \sim 14 \) K and column density of \( \sim 10^{22} \) cm\(^{-2}\).

Three main YSO clusters are identified from the sample of Rebull et al. (2011). Two of these with a great fraction of Class I and flat objects are associated with the molecular cloud of the GoM and the Pelican’s Hat region, which shows low temperature and high C\(^{18}\)O abundance. The third cluster, the Pelican Cluster, is surrounded by the Pelican’s Neck, the Pelican’s Beak, and the Caribbean Islands. Although the Class II sources constitute a higher fraction in the Pelican Cluster, most of the Class I and flat objects appear on the east and west edges of the cluster. This distribution is consistent with the molecular distribution in which the molecular gas in the central area is dispersed and surrounded by clouds with higher molecular temperature and low C\(^{18}\)O abundance. The YSO proportion in the clusters suggests a younger stage of evolution in the most southeastern and northwestern parts of the NAN complex, and an older stage in the center of the Pelican Cluster. If the complex velocity structures in surrounding regions of the Pelican Cluster are indeed the results of feedback from the massive cluster members, the cluster may be triggering the star formation in the molecular cloud across a span of over 5 pc and \( \sim 10 \) km s\(^{-1}\).

We then compare our clump results with the distribution of YSOs, by separating the clumps spatially associated with YSOs from those containing no YSO. The Class III YSOs are not considered, as the Class III catalogue is not complete and their distribution is not associated with molecular clouds. A total of 143 clumps are found to be associated with YSOs. The discrepancies in their physical properties are shown in Figure 28. The clumps associated with YSOs present a higher velocity dispersion, clump size, and excitation temperature, while the discrepancy of the CMF indices is not significant. Further observations with higher signal-to-noise ratio and resolution are needed to extend the limit of mass completeness in CMF comparison.

5. SUMMARY

We have presented the PMODLH mapping observations for an area of 4.25 deg\(^2\) toward the North American and Pelican Nebula molecular cloud complex in \(^{12}\)CO, \(^{13}\)CO, and C\(^{18}\)O lines. The main results are listed below.

The molecule distribution is along the dark lane in the southeast–northwest direction. \(^{12}\)CO emission is bright and extended, while \(^{13}\)CO and C\(^{18}\)O emissions are compact. The channel map shows intricate structures within the complex,
and filamentary structures are revealed. The position–velocity slice along the full length of the cloud reveals a molecular shell surrounding the W80 H II region. Gases of two different temperatures are seen in the distribution of excitation temperature.

The surface density map shows several dense clouds with surface density over \(500 \, M_\odot \, pc^{-2}\) in the complex. We have derived a total mass of \(2.0 \times 10^4 \, M_\odot\) (\(^{13}\)CO) and \(6.1 \times 10^3 \, M_\odot\) (\(^{18}\)O) under the LTE assumption with uniform molecular abundance, and \(5.4 \times 10^4 \, M_\odot\) with the constant CO-to-H\(_2\) factor in the NAN complex. Such a discrepancy in mass may be due to the different extent that the molecules are tracing.

Six regions are discerned in the molecular maps, each with different emission characteristics. Their sizes, column densities, and masses vary with different density tracers. The properties of low temperature, high column density, and high \(^{18}\)O abundance found in the GoM and Pelican’s Hat regions indicate a young stage of massive star formation, while the properties of the Pelican’s Neck, Pelican’s Beak, and Caribbean Islands regions represent a hot, dense, and more evolved environment probably affected by the Pelican Cluster. Only the Caribbean Sea region shows little sign of star formation.

Four filamentary structures are found in the NAN complex. They show complex structures such as a twisted spatial distribution or opposite velocity gradient directions, but these filaments all seem to be in a gravitationally stable state.

We have identified 611 clumps using the ClumpFind algorithm in the NAN complex, which yield a typical size, excitation temperature, and density of \(\sim 0.3 \, pc\), \(13 \, K\), and \(8 \times 10^3 \, cm^{-3}\), respectively. Most of the clumps are non-thermal dominated and in an early evolutionary stage of star formation. The comparison of virial and LTE mass of the clumps indicates that most clumps are gravitationally bound. We obtain a CMF index \(\gamma = 0.95\).

The clumps associated with YSOs present more evolved features compared with those having no association.

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