MOLECULAR GAS AND STAR-FORMATION PROPERTIES
IN THE CENTRAL AND BAR REGIONS OF NGC 6946

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Received 2015 August 30; accepted 2015 November 3; published 2015 December 9

ABSTRACT

In this work, we investigate the molecular gas and star-formation properties in the barred spiral galaxy NGC 6946 using multiple molecular lines and star-formation tracers. A high-resolution image (100 pc) of $^{13}$CO (1–0) is created for the inner 2 kpc disk by the single-dish Nobeyama Radio Observatory 45 m telescope and interferometer Combined Array for Research in Millimeter-wave Astronomy, including the central region (nuclear ring and bar) and the offset ridges of the primary bar. Single-dish HCN (1–0) observations were also made to constrain the amount of dense gas. The physical properties of molecular gas are inferred from (1) the large velocity gradient calculations using our observations and archival $^{13}$CO (1–0), $^{12}$CO (2–1) data, (2) the dense gas fraction suggested by the luminosity ratio of HCN to $^{13}$CO (1–0), and (3) the infrared color. The results show that the molecular gas in the central region is warmer and denser than that of the offset ridges. The dense gas fraction of the central region is similar to that of luminous infrared galaxies/ultraluminous infrared galaxies, whereas the offset ridges are close to the global average of normal galaxies. The coolest and least-dense region is found in a spiral-like structure, which was misunderstood to be part of the southern primary bar in previous low-resolution observations. The star-formation efficiency (SFE) changes by about five times in the inner disk. The variation of SFE agrees with the prediction in terms of star formation regulated by the galactic bar. We find a consistency between the star-forming region and the temperature inferred by the infrared color, suggesting that the distribution of subkiloparsec-scale temperature is driven by star formation.

Key words: galaxies: individual (NGC 6946) – galaxies: ISM – galaxies: star formation – ISM: molecules

1. INTRODUCTION

The star-formation process is intimately related to the physical properties of molecular gas. The physical conditions of molecular gas determine whether stars can form. For example, observations of Galactic molecular gas show that star formation is often associated with dense gas (Lada 1992). This is true even for the galactic-scale observations reported by Gao & Solomon (2004). After the stars form, they heat and recycle materials back into the surrounding molecular gas, reforming the gas, by which the star-formation cycle can start again (e.g., Oey & Massey 1995; Deharveng et al. 2005; Schneider et al. 2012).

In addition to the local gas conditions, extragalactic observations have shown increasing signs that molecular gas and star formation are aware of their galactic-scale environments. The dynamical properties of galaxies (e.g., bar and spiral arms) are responsible for redistributing molecular gas, controlling their formation, evolution, and ability for star formation (Leroy et al. 2008; Koda et al. 2009; Momose et al. 2010; Watanabe et al. 2011; Hughes et al. 2013; Huang & Kauffmann 2015). This is in contrast to previous studies, which generally find that star-formation processes are remarkably similar across galactic regions and galaxies (e.g., Blitz et al. 2007; Bolatto et al. 2008; Lada et al. 2012; Donovan Meyer et al. 2013).

To date, studies of extragalactic molecular gas have mostly used the single molecular line of $^{12}$CO because the excitation conditions of this strong line are easily met. However, the low-density tracer alone is not sufficient to estimate properties that are more intimately related to star formation, e.g., temperature and dense gas fraction. Multimolecular line diagnosis is therefore indispensable in exploring the relation of molecular gas, star formation, and galactic structures to a greater extent.

In this work, we investigate the physical properties of molecular gas and star-formation activity in NGC 6946. These are done by analyzing the newly observed isotopic molecule $^{13}$CO (1–0) (100 pc resolution) and dense gas tracer HCN (1–0), along with other archival molecular data in $^{12}$CO (1–0), (2–1) and star-formation tracers in the optical and infrared wavelengths. This is the first time that this galaxy has been observed in $^{13}$CO with high resolution, and it is one of the very few galaxies for which we can perform isotopic line mapping down to this scale.

NGC 6946 is chosen for this work for a number of reasons. The galaxy is close by at 5.5 Mpc (Tully 1988), allowing us to observe it in high resolution. The face-on galaxy provides excellent viewing perspectives on the galactic structures (Figure 1). The adopted position angle (PA) and inclination are 243° and 33°, respectively (Walter et al. 2008). The galactic disk is characterized by four flocculent spiral arms, three bars, and a circumnuclear ring (Schinnerer et al. 2006; Fathi...
et al. 2007). The outermost oval has a radius of ~7.3 kpc. The dim dust lane (or “offset ridge” downstream of the galactic rotation) of the northern primary bar (~1 kpc) is seen in Figure 1, while the southern dust lane is not clear. The inner region of the primary bar is connected to the nuclear bar with a length of ~400 pc. The nuclear bar wraps around the starburst nucleus, forming a circumnuclear ring with diameter of 20 pc. The disk instability and the formation of these structures have been studied through the Toomre-Q parameter (Ferguson et al. 1998; Meier & Turner 2004; Leroy et al. 2008; Romeo & Fathi 2015). The available data in optical and infrared make the galaxy a prime target to gain insight into the gas and star-formation properties.

This paper is organized as follows. The new observations (molecular lines) and archival data (molecular lines and star-formation tracers) are introduced in Section 2. The results of the new observations and line ratios are presented in Section 3. Galactic regions of interest are defined in Section 4. Section 5 presents the derivation of physical properties of molecular gas. Radial star-formation efficiency (SFE) is discussed in Section 6. Finally, the main points of this work are summarized in Section 7.

2. DATA

We analyze multiple molecular line transitions for investigations of the physical properties of molecular gas and optical and infrared emissions for tracing star-formation activities. We discuss our observations of $^{13}$CO (1–0) and HCN (1–0) line emission in Sections 2.1 and 2.2, respectively. For $^{13}$CO (1–0), we combine single-dish observations (Section 2.1.1) and interferometric observations (Section 2.1.2). Their combination scheme is discussed briefly in Section 2.1.3. The HCN (1–0) data are from single-dish observations alone. Archival multiwavelength data are also used in our analyses and are presented in Section 2.3. Table 1 presents a summary of the data used in this study. In Section 2.4, we will discuss the physical properties that each of these emission traces to guide readers.

2.1. $^{13}$CO (1–0) Observations and Data Reduction

Among the three data sets of $^{13}$CO from the NRO45 Combined Array for Research in Millimeter-wave Astronomy (CARMA) observations, we refer to the combined data cube as the cube (or data or map) in this study. The other two will be referenced explicitly as CARMA data and NRO45 data.

2.1.1. Single-dish Observations

The single-dish observations of $^{13}$CO (1–0) (hereafter $^{13}$CO) were made with the Nobeyama Radio Observatory 45 m telescope (NRO45) in 2013 January–February. The observations cover a $160^\prime\times 160^\prime$ area with $PA = 0^\circ$, centering at the galactic center (see the box in Figure 1). The observed area includes important galactic structures, such as the galactic center, galactic bar, and the inner parts of spiral arms. The effective beam size of NRO45 is 20′ at 110.2 GHz for the on-the-fly (OTF) mapping mode (Sawada et al. 2008), which ensures an accurate relative flux calibration over the map.

The dual-polarization receiver TZ (Asayama & Nakajima 2013; Nakajima et al. 2013) was connected to the digital spectrometer Spectral Analysis Machine for the 45 m telescope (SAM45). We observed with a frequency resolution of 488.28 kHz (1.3 km s$^{-1}$ at 110 GHz) and an effective bandwidth of 1600 MHz (4356 km s$^{-1}$). The typical system noise temperature ($T_{sys}$) was 160–180 K.

Each OTF map contains 33 scans in the $x$ or $y$ directions and took a total of about 31 minutes. Each scan was 20 s long with an interval of adjacent scans of 5′. An OFF point 8′ away from the map center was observed every two scans for the standard ON-OFF calibration. Each ON-OFF cycle (ON-ON-OFF) took 1.5 minutes. Before the observation of each map, we corrected the telescope pointing by observing a point source, the SiO maser T-Cep. The pointing observations were performed at 43 GHz with receiver S40. In addition, the Galactic object S140X was observed at the frequency of 13CO$^{*}$ at 110 GHz and an effective bandwidth of 1600 MHz (4356 km s$^{-1}$). The main beam efficiency of NRO45 is 40% for the conversion from the antenna temperature ($T_A^*$) to the main beam temperature ($T_{mb}$), i.e., $T_{mb} = T_A^*/0.4$.

2.1.2. Interferometric Observations

Observations with CARMA were made in 2009 February–May as a part of the CARMA-Nobeyama Nearby-galaxies
The velocity channel width is 2.6 km s\(^{-1}\) respectively. The 13CO and 12CO emission appears to extend over about 60'' × 80'' (RA × decl. directions) in the low-resolution NRO45 map, which is resolved into more detailed structures in the CARMA-alone map.

### Notes

- OTF observations.
- After compering with single-dish data.
- Position-switch observations.

(CANON) CO(1–0) survey (J. Koda et al. 2015, in preparation). Some results from the 12CO (1–0) emission were published in Donovan Meyer et al. (2012). The CANON observations included the 13CO (1–0) line emission in the lower-side band of receiver, and hence 13CO (1–0) and 12CO (1–0) were observed simultaneously.

CARMA consists of six 10 m and nine 6 m antennas. We employed the 19-point hexagonal mosaic displayed in Figure 1, which covers the central part of NGC 6946. The resultant size of the map is about 160'' in diameter (~4.3 kpc), with the sensitivity uniform up to about 120'' in diameter (the central seven pointings) and then declining to 1/2 at the 160'' in diameter.

Three narrow bands were used in the observations of 13CO (1–0), resulting in the total bandwidth of ~108 MHz. The velocity channel width is 2.6 km s\(^{-1}\). The total on-source integration time was about 21 hr including calibrators (Donovan Meyer et al. 2012). The bandpass, gain, and flux calibrators are 1715 + 096, 2015 + 372, and MWC349, respectively.

The CLEAN procedure is employed for deconvolution using the MIRIAD package (Sault et al. 1995). The 13CO emission is often faint, and applying a spatial mask at prospective emission regions usually helps the deconvolution process. Since 12CO is much stronger than 13CO, we expect 12CO emission to always be associated with 13CO emission. We therefore made a map of 12CO first, made a mask in channel maps, and used the mask in CLEANing the 13CO map. The final cube of 13CO has a velocity width of 10 km s\(^{-1}\) and the rms noise of 11 mJy beam\(^{-1}\). The beam size is 3''29 × 3''08 (89 pc × 83 pc) with PA = −71°31.

We first compare the maps from NRO45 alone and CARMA alone. The integrated intensity maps of 13CO created from NRO45-alone and CARMA-alone data are presented in the upper left and upper right panels of Figure 2, respectively. Note that the NRO45 map covers a larger area to show a larger extent of 13CO emission. Overall, NRO45 and CARMA capture similar structures with some differences due to the different spatial resolution (20'' versus 3'') and the sensitivity to extended components. The 13CO emission appears to extend over about 60'' × 80'' (RA × decl. directions) in the low-resolution NRO45 map, which is resolved into more detailed structures in the CARMA-alone map.

### 2.1.3. Combination Procedure of 13CO Data

We followed Koda et al. (2011) to combine the single-dish and interferometer 13CO data. We converted the NRO45 map into visibility data points and then inverted the CARMA plus NRO45 visibilities together to make dirty channel maps. We flagged the baselines >4 kλ (~10 m) from the NRO45 visibilities because the NRO45 data become noisier at the longer baselines and CARMA covers the long baselines sufficiently. The dirty maps were CLEANed with MIRIAD. The final combined cube has the velocity resolution of 10 km s\(^{-1}\) with the noise level of 14 mJy beam\(^{-1}\). The synthesized beam is 3''84 × 3''61 (104 pc × 97 pc) with PA = −71°38.

We will discuss the resultant map (our default) in Section 3, but for clarity in the following section, the lower-left panel of Figure 2 shows the combined 13CO map (integrated intensity map).

### 2.1.4. Flux Recovered in the Combined Map

The fluxes are very consistent between the NRO45 and CARMA+NRO45 cubes. To compare the two, we smoothed the combined cube to the 20'' resolution, the same as that of the NRO45 cube. Figure 3(a) compares the average spectra over the central rectangle area (30'' × 70'') stretched along the bar (north–south direction). Thick-line, thin-line, and shadowed histograms show the spectra of the NRO45, CARMA, and CARMA+NRO45 cubes, respectively. The NRO45 and CARMA+NRO45 spectra are very similar overall, while the CARMA spectrum has a flux only about 50% of the NRO45 one. The total integrated flux of the NRO45 and CARMA+NRO45 cubes are about 240 Jy, while the CARMA data have the total flux of ~120 Jy, again only 50%; therefore, the combination of interferometer and single-dish data is very important. Figure 3(b) also shows a similar comparison, but within a 20'' aperture at the center. The recovered flux by CARMA alone is ~80% in total flux with respect to NRO45.

### 2.2. HCN (1–0) Observations and Data Reduction

The observations in HCN(1–0) were carried out in 2013 January using NRO45. We observed only three selected positions in the HCN(1–0) line emission because this emission is weak (e.g., \(I_{\text{HCN}}/I_{\text{CO}} < 0.3\) in galactic disks; Matsushita et al. 2010). These pointed observations reveal the amount of
dense gas in the regions of interest. The three positions are the galactic center at \((20^{\text{h}}34^{m}52^{s}.3, +60^{\circ}9^{\prime}14^{\prime\prime})\) and two off-center regions at \((20^{\text{h}}34^{m}51^{s}.3, +60^{\circ}9^{\prime}38^{\prime\prime})\) and \((20^{\text{h}}34^{m}52^{s}.9, +60^{\circ}8^{\prime}55^{\prime\prime})\) (circles in the lower-left panel of Figure 2).

We used the receiver TZ and spectrometer SAM45 and employed the position-switch mode of observations. The frequency resolution is 488.28 kHz \((1.6 \text{ km s}^{-1} \text{ at } 88.6 \text{ GHz})\), and the effective bandwidth is 1600 MHz \((\sim 5416 \text{ km s}^{-1})\). An OFF point 8′ away from the target was observed every 15 s for the ON-OFF calibration. We checked telescope pointings every 45 minutes with the SiO maser T-cep. The \(T_{\text{sys}}\) was about 140 K during the observations. A standard flux calibrator S140 was observed once per day. The total on-source integrated time is about one hour at each position. The NRO45 beam size at the HCN (1–0) frequency is about 19″, roughly comparable to the beam size at CO of 20″ after regridding (smoothing) the OTF data onto the grid of the final data cube.

The data reduction was carried out with the NEWSTAR package developed at the Nobeyama observatory. We subtracted spectral baselines from each spectrum using a linear fit
and flagged some bad spectra (with nonflat baselines). We binned the spectra, and the final spectra have a velocity resolution of 13 km s\(^{-1}\). We detected the emission from the galactic center at an 18\(\sigma\) significance and 5–6\(\sigma\) significance at the off-center regions.

### 2.3. Archival Data

We analyze \(^{12}\text{CO} (1–0), \text{^{13}CO} (2–1), \text{^{13}CO} (1–0), \text{HCN} (1–0), \text{H}_2\), and 70 and 160 \(\mu\)m to probe the physical conditions of molecular gas in NGC 6946. The \(^{12}\text{CO} (1–0)\) and HCN (1–0) emission data are from our own observations as discussed above, and \(^{13}\text{CO} (1–0)\) and \(^{12}\text{CO} (2–1)\) are obtained from the CANON Survey (Donovan Meyer et al. 2012; Koda et al. 2015, in preparation) and the HERA CO-Line Extragalactic Survey (HERACLES; Leroy et al. 2009), respectively.

To investigate star-formation activities, we use the archival data of \textit{Spitzer} 24 \(\mu\)m and H\(\alpha\) recombination line emissions. The 24 \(\mu\)m and H\(\alpha\) images are taken from the \textit{Spitzer} Infrared Nearby Galaxies Survey (SINGS; Kennicutt et al. 2003). We also use the 70 and 160 \(\mu\)m images from the Key Insights on Nearby Galaxies: a Far-Infrared Survey with \textit{Herschel} (KINGFISH; Kennicutt et al. 2011) to infer the trend of temperature of dust and gas.

### 2.4. Physical Properties Traced by Each Emission

This study compares multiwavelength data to investigate the physical conditions of gas and star-formation activities in NGC 6946. It is perhaps useful to summarize what each of these multiwavelength data sets traces physically.

#### 2.4.1. Molecular Line Emissions

The \(^{12}\text{CO}(1–0)\) line is often used to trace the amount of bulk molecular gas; \(^{12}\text{CO}\) is the second most abundant molecule after H\(_2\). The temperature equivalent to the first energy level of rotational transition is \(\sim 5.5\) K, so the \(J = 1\) level is always populated very well for the typical temperature of molecular gas (\(\sim 10\) K). Its typically high opacity prevents photons from escaping efficiently from the emitting area, which drops the effective critical density for excitation low (\(\sim 300\) cm\(^{-3}\); Scoville & Solomon 1974). The average density within molecular clouds is comparable to this density (Solomon et al. 1987), so the bulk of molecular gas within molecular clouds emits \(^{12}\text{CO}(1–0)\) emission efficiently.

The temperature equivalent to the \(J = 2\) energy level is \(\sim 15\) K, slightly above the typical gas temperature, and hence \(^{12}\text{CO} (2–1)\) is sensitive to slight enhancements in gas temperature or density of the bulk molecular gas (Koda et al. 2012). Note that \(^{12}\text{CO}(1–0)\) is often used as a tracer of molecular gas mass (Bolatto et al. 2013, and references therein), even though \(^{12}\text{CO}\) is generally optically thick. The velocity dispersion of molecular clouds is almost always larger than the thermal line width, and, in fact, this optically thick line can trace the entire volume within the clouds and thus their mass. We use the \(^{12}\text{CO}(1–0)\) emission for calculation of molecular gas mass.

The \(^{13}\text{CO} (1–0)\) emission (hereafter \(^{13}\text{CO}\)) is also used to trace bulk molecular gas. It is typically optically thin compared to \(^{12}\text{CO}(1–0)\), so its effective critical density (\(\sim 2 \times 10^3\) cm\(^{-3}\)) is an order of magnitude greater than that of \(^{12}\text{CO}\), tracing slightly denser gas. The abundance ratio of \(^{12}\text{CO}\) to \(^{13}\text{CO}\) is about 40–60, so \(^{13}\text{CO}\) emission is significantly weaker than \(^{12}\text{CO}\) emission.

The HCN (1–0) emission (hereafter HCN) is often used as a tracer of star-forming dense cores within molecular clouds. It has a high critical density (\(\sim 10^5\) cm\(^{-3}\)) and the HCN emission, even unresolved, should be coming selectively from the very dense regions within molecular clouds. The connection between these dense regions and star-formation activities are seen in the linear correlation between HCN and tracers of star-formation rate (SFR). We use HCN to constrain the amount of dense gas. Enhanced HCN emission around active galactic nuclei (e.g., Imanishi et al. 2007; Izumi et al. 2013) may be a source of confusion when the galactic center is the focus of study, but the mechanism of the enhancement is irrelevant here because NGC 6946 has no appreciable supermassive black hole (Kormendy et al. 2007, 2010).

#### 2.4.2. H\(\alpha\) and Infrared Emissions

H\(\alpha\) and infrared emissions are often used to trace the intensity of star formation. Both types of emissions are the second product of recently formed young stars, with H\(\alpha\) emission from the gas ionized by UV photons from young, massive stars and by infrared radiation, such as the 24 \(\mu\)m emission tracing the thermal radiation from dust heated...
predominantly by young stars at the age up to $\sim 10$ Myr (Calzetti et al. 2005).

Each emission has its own advantages and disadvantages in estimating the SFR. H$\alpha$ typically provides a high spatial resolution but suffers from dust extinction. The bottleneck of current infrared data is its relatively low spatial resolution, though the extinction is not so much a problem at the infrared wavelengths.

The combination of the two may complement each other and provide a more accurate estimate of SFR (e.g., Calzetti et al. 2005; Kennicutt et al. 2007; Calzetti 2012), although the spatial resolution may be an issue here since it needs to be adjusted to the lowest infrared resolution. Here, we use 24 $\mu$m and H$\alpha$ emissions to gauge star-formation activities.

Infrared color is used to infer dust temperature. Young massive stars contribute to the spectral energy distribution (SED) at shorter wavelengths, producing a peak around $\sim 60$ $\mu$m, while low-mass stars contribute to the SED at longer wavelengths, generating another peak around $\gtrsim 160$ $\mu$m (Calzetti 2012). Therefore, the ratio of the fluxes around the two peaks provides a probe of dust and gas temperature. In this work, we use a 70–160 $\mu$m flux ratio or color to trace the temperature variation.

3. OBSERVATIONAL RESULTS

3.1. $^{13}$CO Observations

3.1.1. Channel Map

The channel maps of $^{13}$CO are displayed in Figure 4 with red contours, and the $^{12}$CO contours (black) are also plotted for reference (the $^{12}$CO data also include CARMA and NRO45 data). The galactic center is marked with a cross in each channel. There is a central peak around the galactic center. The central peak has a velocity width of $\sim 180$ km s$^{-1}$, ranging from $-34$ to 149 km s$^{-1}$. Apart from the central component, two elongated structures emerging from the galactic center are seen, extending toward the north and the south, respectively. Both sides show sharp velocity gradients across the elongated structures. Such a pattern is commonly seen in galactic bars (e.g., Koda & Sofue 2006). Emission in the northern region emerges from $\sim -14$ km s$^{-1}$, spreading over $\sim 112$ km s$^{-1}$. Emission in the southern region emerges from $\sim -39$ km s$^{-1}$, spreading over $\sim 110$ km s$^{-1}$.

The spatial and velocity distributions of $^{13}$CO and $^{12}$CO emission are similar in all channels. All $^{13}$CO peaks have counterparts in $^{12}$CO. This is a natural result, as mentioned in Section 2.4. In contrast, $^{13}$CO is absent at some $^{12}$CO peaks (e.g., 67 km s$^{-1}$). This is due to either the detection limit or an insufficient density for $^{13}$CO excitation.

3.1.2. Integrated Intensity Maps

The CARMA+NRO45 map clearly shows the central component in details, resolving the central concentration elongated toward the northwest to southeast directions. The semimajor axis of the elongation is about 8″ ($\sim 220$ pc), corresponding to the secondary (nuclear) bar formed via local gravitational instability in the disk (Elmegreen et al. 1998; Schinnerer et al. 2006; Fathi et al. 2007; Romeo & Fathi 2015). The structure inside the secondary bar is not resolved in our map. The emission appears to extend toward the north from the edge of this elongation, reaching the radius of $\sim 40''$ toward north. We call this extension the “northern ridge,” which has a bright peak near the CARMA field of view.

The $^{12}$CO map from CARMA+NRO45 is displayed in the lower-right panel of Figure 2 for comparison. The $^{13}$CO and $^{12}$CO maps are generally similar, though $^{12}$CO shows more continuous extension overall. For example, the emission extends smoothly along the northern ridge in $^{12}$CO, but shows a gap in $^{13}$CO at around the radius of 16″–18″, which is between the central concentration and the northern ridge. The lack of $^{13}$CO emission could be due to an insufficient sensitivity for detection of this weak line, but we also point out that the level of $^{13}$CO emission must be lower than what is expected in assuming a $^{12}$CO/$^{13}$CO line ratio of 15, i.e., the average over the area of significant $^{13}$CO detection within the northern ridge. Assuming this ratio, the expected $^{13}$CO flux is $\sim 1.8$ Jy beam$^{-1}$ km s$^{-1}$ in this gap, which should be detected at the 4$\sigma$ significance. Therefore, the $^{12}$CO/$^{13}$CO ratio is enhanced at the connection between the central concentration and the northern ridge, suggesting a change of molecular gas properties along the bar. Such an enhancement has also been reported in the strong bar galaxy NGC 7479 by Hütttemeister et al. (2000).

The main difference between the CARMA+NRO45, NRO45-alone, and CARMA-alone maps appears at the south side of the galaxy. The CARMA+NRO45 maps show a curved spiral-like pattern to the southeast of the center that appears as an extended emission in the NRO45 map but appears only as distributed or unconnected emission peaks in the CARMA map. Some of the extended emission is not detectable in the CARMA-alone map, which is recovered by the combination.

3.2. HCN Observations

Figures 5(a), (b), and (c) compare HCN spectra against $^{12}$CO and $^{13}$CO spectra (NRO45 alone) at the center, north off-center, and south off-center regions, respectively. Their overall shapes are similar to each other, except that the spectra at the south off-center position show a slight difference. At this position the HCN spectrum shows a single peak, while the two CO lines show two peaks at $\sim 40$ and 80 km s$^{-1}$, suggesting that CO and HCN trace different gas components.

The HCN integrated intensity is $18.9 \pm 1.4$, 4.7 ± 0.8, and 4.2 ± 0.8 K km s$^{-1}$ at the center, north, and south off-center regions, respectively.

The luminosity ratios of $L_{\text{HCN}}/L_{\text{CO}}$ of the galactic center, north, and south off-center regions are 0.111 ± 0.011, 0.065 ± 0.013, and 0.051 ± 0.012, respectively. The luminosity ratios of the off-center positions are close to the global average values of normal galaxies, while $L_{\text{HCN}}/L_{\text{CO}}$ of the central region lies between the mean value of luminous infrared galaxies (LIRGs) and ultraluminous infrared galaxies (ULIRGs) (Gao & Solomon 2004), where the definitions of LIRG and ULIRG are $10^11 L_{\odot} < L_{\text{IR}} < 10^{12} L_{\odot}$ and $L_{\text{IR}} > 10^{11.9} L_{\odot}$, respectively.

3.3. Line Ratio of CO Lines

The emission line ratio often provides an idea of the physical properties of molecular gas. The intensity ratio ($R_{\odot}$) of $^{12}$CO to $^{13}$CO is presented in Figure 6. This ratio varies by a factor of three—the maximum ($\sim 17$) around the galactic center to the minimum ($\sim 6$) in the spiral-like ridge, which covers the large range observed in typical Galactic molecular clouds (<10) to
starburst galaxies and galaxy mergers (10–20, though sometimes >10–20; Solomon et al. 1979; Aalto et al. 1995; Taniguchi & Ohyama 1998; Paglione et al. 2001; Tan et al. 2011).

A variable 12CO (2–1)/(1–0) ratio (R_{21}) is also observed in NGC 6946. The left panel of Figure 7 presents the R_{21} map of the entire galaxy. Because there is only the single-dish 12CO (2–1) image, we calculate R_{21} with the single-dish 12CO (1–0). The R_{21} map has a resolution of 20", which is the resolution of the NRO45 data of 12CO (1–0). The ratio map shows a central oval with R_{21} ≈ 1. The orientation of this oval...
is consistent with the unresolved minibar. The ratio $R_{31}$ is about 0.5–0.8 at the spiral arms and 0.3–0.5 at the inter-arm regions. These ratios are comparable to that in the Milky Way and nearby galaxies (e.g., Handa et al. 1997; Oka et al. 1998; Sawada et al. 2001; Koda et al. 2012).

The right panel of Figure 7 compares the spatial distribution of $R_{31}$ and the star-forming regions traced by Spitzer 24 μm. The high $R_{31}$ is spatially correlated with the location of stars.

4. GAS STRUCTURES FROM CO OBSERVATIONS

The morphology of molecular gas in NGC 6946 resembles the typical barred spiral galaxies (e.g., Sheth et al. 2002; Koda & Sofue 2006). Barred spiral galaxies often show a central concentration of gas and offset ridges that extend from the central concentration along the leading side of the bar. Such structures are often reproduced in numerical simulations (e.g., Athanassoula & Bureau 1999) and analytical gas orbit models (Wada 1994; Sakamoto et al. 1999; Koda et al. 2002; Koda & Sofue 2006). The bar of this galaxy runs in the north–south direction in an optical image. The CO map shows the central concentration with a major axis of ~20′ (~540 pc) and two ridges with length ~20′–30′, running from the central concentration toward the north and south directions, with the southern ridge appearing fragmented.

For clarity in the rest of our discussions, we define molecular gas structures based on the morphology in the CO map. We call the central concentration (oval structure with the long extension of 20′ elongated toward the southeast–northwest direction) as the central region. This definition of the central region includes the secondary minibar as well as the galactic center (lower-left panel of Figure 2). The two ridges extending from the central region toward north and south are called the northern ridge and southern ridge, respectively. From a closer look at the distribution and kinematics, we notice that there is an additional component superposed on the southern ridge. This component resembles a spiral arm, originating from the northeast side of the central region and curving toward the south (around −14 to 16 km s$^{-1}$ in the channel map of Figure 4). We call this structure the south spiral.

The molecular gas of the south spiral may be spatially distributed because the emission is not prominent in the CARMA-alone map, but it does appear very clearly in the CARMA+NRO45 map. The south spiral has a lower $R_{10}$ (Figure 6) than other defined structures. The southern ridge appears fragmented, and there are multiple emission peaks in the region. Figure 6 shows that these peaks have high $R_{10}$, which are comparable to those in the northern ridge. Therefore, we consider the southern ridge as a counterpart of the northern ridge, even though the southern ridge is more fragmented.

In what follows, we will separate our analyses as spatially resolved analyses and unresolved analyses. For the former, we separate the galactic structures as defined above, while for the latter we average them out with a radial bin and discuss only radial variations.

5. PHYSICAL PROPERTIES OF MOLECULAR GAS

In order to constrain the spatially resolved temperature and density of molecular gas, we adopt the one-zone large velocity gradient (LVG) model (Goldreich & Kwan 1974; Scoville & Solomon 1974). We briefly explain the LVG model (Section 5.1) and apply it to individual regions (Section 5.2). We then compare the derived gas physical properties with color in the infrared.

5.1. The LVG Model

Molecular emissions depend primarily on three parameters: kinetic temperature ($T_k$) and volume density ($n_H$) determine the excitation condition, and the optical depth $\tau$ (or alternatively the column density $N_{CO}$ per unit velocity $dv$, i.e., $N_{CO}/dv$) is important for the radiative transfer. In addition, photon trapping is usually included, in which a large $\tau$ effectively reduces the spontaneous emission rate and affects the excitation condition as well. The LVG model calculates emission line strengths when ($N_{CO}/dv$, $T_k$, $n_H$) are given. In reverse, we constrain ($T_k$, $n_H$) using the observed emission line ratios, in our case $^{12}$CO(1–0), $^{12}$CO(2–1), and $^{13}$CO(1–0). We employ the LVG code used in Koda et al. (2012) with CO–H$_2$ collisional cross sections from Yang et al. (2010).

For simplicity, we fix a possible range of log ($N_{CO}/dv$) = 16.6–17.3 cm$^{-2}$ (km s$^{-1}$)$^{-1}$ as found in the Galaxy and M51 (Solomon et al. 1987; Rodriguez-Fernandez et al. 2006; Schinnerer et al. 2010; Koda et al. 2012). NGC 6946 has a similar range based on the resolved giant molecular cloud analysis (Donovan Meyer et al. 2012). The abundance ratios, [$^{12}$CO/H$_2$] and [$^{13}$CO]/[$^{12}$CO], are fixed to the Galactic values and are 8.0 × 10$^{-5}$ and 60, respectively (Langer et al. 1982; Schinnerer et al. 2010; Koda et al. 2012).

Figure 8 demonstrates the solutions from LVG for (a) $R_{10}$ and (b) $R_{31}$. The gray and black lines are for log ($N_{CO}/dv$) = 16.6 and 17.3 cm$^{-2}$ (km s$^{-1}$)$^{-1}$, respectively.

The LVG results appear nonlinear in Figure 8, due to a mixture of different physical factors. For example, the higher abundance of $^{12}$CO over $^{13}$CO results in a significant difference in optical depth ($\tau_{2CO} \gg \tau_{3CO}$). Hence, photons from $^{12}$CO are absorbed (trapped) more dominantly in the region where they are emitted, resulting in a lower effective spontaneous emission rate and thus in a lower critical density (~300 cm$^{-3}$ over ~2000 cm$^{-3}$). The difference in the critical densities
changes their line ratio $R_{01}$ dramatically up to $n \sim 2000 \text{ cm}^{-3}$. Beyond this density, both $^{13}$CO and $^{12}$CO excitations are saturated and optically thick, and $R_{01}$ does not depend on the density (Figure 8(a)). An additional complexity is that the optical depth depends on velocity line width, as well as the column density at each $J$ level (which depends on temperature and density). The Doppler broadening of molecular gas is typically wider than the thermal line width, and thus photons from behind may not be absorbed by the gas in front at a different velocity. The LVG models take these into account and show the nonlinear lines in Figure 8. Observations of $R_{01}$ and $R_{21}$ enclose an area in the parameter space and give constraints on the physical parameters.

5.2. Applications to Individual Regions

Figure 9 shows constraints from the observed $R_{01}$ and $R_{21}$ in the central region, ridges, and south spiral, and the enclosed areas (gray) indicate the possible ranges of gas temperature and density. We adopted $\log(N_{\text{CO}}/dv) = 16.6–17.3$ as its possible range. The adopted line ratios and the derived temperatures and densities are show in Table 2.

5.2.1. The Central Region

At the central region, either temperature or density needs to be high: $(T_H > 40 \text{ K}, n_H \sim 10^{3.5} \text{ cm}^{-3})$ or $(T_H \approx 20–35 \text{ K}, n_H \gtrsim 10^{10.5–11.5} \text{ cm}^{-3})$ to satisfy $R_{01} \sim 17$ and $R_{21} \sim 1.0$ (Figure 9(a)). These solutions can coexist, and, indeed, a presence of a range of gas temperature and density was suggested by Mangum et al. (2013) from their ammonia (NH$_3$) observations (i.e., molecular cloud thermometer). Their reported temperatures, 25 $\pm$ 3 K and 50 $\pm$ 10 K, are consistent with ours.

The derived densities ($\gtrsim 3 \times 10^3 \text{ cm}^{-3}$) are an order of magnitude higher than the critical density of CO(1–0) excitation, indicating an overall high density in the central region. Although the structures are not resolved with our large beam (hundreds of parsecs), the average high density likely indicates that dense cores and associated star formation exist in this environment. In fact, the observed $L_{\text{HCN}}/L_{\text{CO}}$ ratio of the central region is consistent with that of LIRGs and ULIRGs (Section 3.2), implying that the fraction of dense gas in this region is likely similar to that in starburst galaxies.

5.2.2. The Ridges and the South Spiral

Molecular gas at the ridges are likely cooler and less dense than the galactic center. The line ratios of $R_{01} \approx 15$ and $R_{21} \approx 0.8$ indicate an average temperature and density of $>15–20 \text{ K}$ and $10^{2–3} \text{ cm}^{-3}$, respectively (Figure 9(b)). The southern ridge cannot be clearly identified in the single-dish $R_{21}$ map, but its gas composition may resemble the northern ridge, due to the compatible $L_{\text{HCN}}/L_{\text{CO}}$ and $R_{01}$. Assuming that $R_{21}$ of the southern ridge is $\sim 0.8$ as that of the northern ridge, and its $R_{01}$ is about 12, the LVG calculations suggest $T_H > 10 \text{ K}$ and $n_H \sim 10^{2–3} \text{ cm}^{-3}$ (Figure 9(c)).

The south spiral likely has the lowest temperature and density among the regions of interest. Previous HCN mapping observations reported that its $L_{\text{HCN}}/L_{\text{CO}}$ is considerably lower than that in the ridges and the center (Levine et al. 2008), indicating that the overall density and the fraction of dense gas is unlikely larger than in those areas, i.e., $< 10^3 \text{ cm}^{-3}$. With $R_{01} \approx 7$, Figure 9(d) therefore suggests that the $R_{21}$ is likely less than 0.6. These ratios give the solution of temperature of $T_H < 20 \text{ K}$.

5.3. Relative Temperature from Infrared Color

Dust temperature provides an indirect measure of gas temperature. Since the LVG calculations only suggest lower or upper limits of gas temperatures, due to the nonclosed contours, we use independent methods to constrain the relative temperatures among the regions of interest. Gas temperature ($T_g$) and dust temperature ($T_d$) are not coupled except in very high density regions, but they are positively correlated (e.g., Forbrich et al. 2014). We therefore assume that $T_d$ can be used to infer the variation of $T_g$.

The infrared color of the 70–160 $\mu$m flux ratio ($S_{70}/S_{160}$) is used to infer the relative $T_g$ among the regions of interest through the SED implied $T_d$, i.e., $S_{70}/S_{160}$ increases with $T_d$ (and therefore $T_d$ based on the assumption above). The $S_{70}/S_{160}$ map of the entire galaxy is shown in Figure 10(a), while Figure 10(b) displays the color map of the central 1$'$. The flux ratio is shown with both color scale and contours. The galactic center is marked with a plus symbol. The black circle denotes the central 1$'$. Two multiplication signs (×) indicate the positions of HCN observations at the ridges.
The relative temperatures among the regions of interest are consistent with the results of LVG calculations. The ratio \( S_{70}/S_{160} \) peaks at the galactic center (\( \sim 0.31 \)), indicating the warmest gas in the galaxy. The northern ridge (\( S_{70}/S_{160} \approx 0.16 \)) is slightly warmer than the southern ridge and the south spiral (\( S_{70}/S_{160} \approx 0.13 \)).

The temperature distribution of NGC 6946 is likely driven by star formation. A spatial correlation between \( S_{70}/S_{160} \) and the star-forming regions traced by 24 \( \mu \)m emissions is observed at the central region. The northern and southern ridges characteristic of two stronger 24 \( \mu \)m emissions (around the positions of HCN observations) have higher temperatures than their surroundings, while the south spiral has a lack of 24 \( \mu \)m emission.

6. RADIAL SFE

We discuss the star-formation activity in terms of the radial profile of SFE. A radial variation of SFE is adopted since the star-formation regions do not coexist with molecular gas but shift azimuthally toward the leading sides of the offset ridges (dust lanes), as has been reported in many galaxies (e.g., Reynaud & Downes 1998; Sheth et al. 2000, 2002; Asif et al. 2005). We therefore assume that the star-formation regions travel simply azimuthally, and these two postulations can be correlated by azimuthally averaging the properties at the same radius.

The definition of SFE is the number of stars formed per year and can be formulated as \( \text{SFR}/M_{\text{H}_2} \). The SFR is calculated with the luminosity–SFR relation suggested by Calzetti et al. (2007):

\[
\text{SFR} \left[ \frac{M_\odot \text{yr}^{-1}}{M_\odot} \right] = 5.45 \times 10^{-42} \times \left( \frac{L(H\alpha)_\text{obs}}{\text{erg s}^{-1}} + 0.031 \frac{L(24)}{\text{erg s}^{-1}} \right) \times \cos i,
\]

where \( L(H\alpha)_\text{obs} \) and \( L(24) \) are the observed luminosity of H\( \alpha \) and 24 \( \mu \)m, respectively, and \( i \) is inclinations of the galaxy. The molecular gas mass \( M_{\text{H}_2} \) is derived with \( ^{12}\text{CO} \) (1–0) because it traces the entire volume of molecular gas and requires fewer assumptions in the derivation. The conversion between \( ^{12}\text{CO} \) (1–0) flux and \( M_{\text{H}_2} \) is

\[
\frac{M_{\text{H}_2}}{M_\odot} = 4 \times 10^{-17} \times \frac{S_{\text{CO}}}{\text{Jy km s}^{-1} \text{Mpc}^{-1}} \times \frac{D^2}{\text{K km s}^{-1}} \times \frac{X_{\text{CO}}}{\text{K km s}^{-1}},
\]

where \( S_{\text{CO}} \) is the flux of \( ^{12}\text{CO} \) emission, \( D \) is the distance of the galaxy, and \( X_{\text{CO}} \) is the CO-to-H\( _2 \) conversion (the only assumption in the calculation). A conversion factor of \( X_{\text{CO}} = 1.2 \times 10^{20} \text{cm}^{-2} \text{(K km s}^{-1})^{-1} \) is adopted in this work. The value is derived from the virial mass of molecular clouds by Donovan Meyer et al. (2012). The SFR and \( M_{\text{H}_2} \) are sampled with a step of 5° (135 pc) to calculate the radial SFE.

We calculate the radial SFE in the inner \( \sim 70'' \) (\( \sim 2 \text{kpc} \)) of NGC 6946. Figure 11 visualizes the representative annuli and shows the radial extent of galactic structures. The central unresolved region (\( r < 10'' \)) is enclosed within the inner ellipse. This region is discarded in the radial profile of SFE because it is greatly unsolved, but we still calculate the average SFE in this region to be \( \sim 10^9 \text{yr}^{-1} \) for comparison. The middle annulus (\( 10'' < r < 37'' \)) corresponds to the offset ridges. Spiral arms emerging from the offset ridge end in the outer annulus of \( 37'' < r < 70'' \).

Figure 12 illustrates the radial SFE. Dashed, thin solid, and thick solid curves represent the SFE of the northern and southern sides and their average, respectively. The corresponding galactic features of each radii are indicated at the upper side of the figure. The SFE varies by about five times within the range of \( \sim 10^{-10} \text{–} 10^{-9} \text{yr}^{-1} \). This range is comparable to that of nearby disk galaxies seen in a pixel-based analysis (e.g., Bigiel et al. 2008; Leroy et al. 2008; Huang & Kaufmann 2015).

At the ridges, the SFE of the north side is higher than the south side by about two times, but the radial variations of the two sides are similar. The lowest SFE (\( \sim 3 \times 10^{-10} \text{yr}^{-1} \)) occurs at the inner ridges, then increases to the local maximum.
at the ridge ends. The peak SFE is as high as \( \sim 1.5 \times 10^{-9} \) yr\(^{-1}\) at the northern ridge end, about two times higher than that of the south side. The variation is consistent with the prediction in terms of the dust-lane shocks. Dust-lane shocks increase toward the south side. The variation is consistent with the prediction in terms of the dust-lane shocks. Dust-lane shocks increase toward the south side.

Figure 9. Results of LVG calculations with combinations of \( R_{0} \) (dashed curves) and \( R_{21} \) (solid curves) for the defined galactic features in Section 4. In each panel, the gray and black curves represent \( \log(N_{\text{CO}}/d^3) = 16.6 \) and \( 17.3 \) cm\(^{-2}\) (km s\(^{-1}\))\(^{-3}\), respectively. Possible solutions of \( T_{k} \) and \( n_{\text{H}_2} \) are enclosed within the curves of two line ratios and their two \( \log(N_{\text{CO}}/d^3) \) highlighted with gray shadows. (a) Results of the central region where the average \( R_{0} = 17 \) and the average \( R_{21} = 1.0 \). (b) Results of the northern ridge where the average \( R_{0} = 15 \) and the average \( R_{21} = 0.8 \). (c) Results of the southern ridge where the average \( R_{0} = 12 \) and the average \( R_{21} = 0.8 \). (d) Results of the south spiral where the average \( R_{0} = 7 \) and the average \( R_{21} \leq 0.6 \).

Table 2

| Region             | \( R_{0} \) | \( R_{21} \) | \( T_{k}, n_{\text{H}_2} \) | \( I_{\text{HCN}} \) | \( L_{\text{HCN}}/L_{\text{CO}} \) |
|--------------------|-------------|-------------|-----------------------------|-----------------|------------------------|
| Central region     | 17          | \( \sim 1.0 \) | \( (\sim 40 \), \( (\sim 10^{3.3} \) cm\(^{-3}\)) \) | 18.9 \pm 1.4     | 0.111                  |
| Northern ridge     | 12–20       | \( \sim 0.8 \) | \( (\sim 20–35 \, 10^{2.3–4.7} \) cm\(^{-3}\)) \) | 4.7 \pm 0.8     | 0.065                  |
| Southern ridge     | 10–13       | \( \sim 0.8 \) | \( (\sim 15–20 \, 10^{2.3–4.7} \) cm\(^{-3}\)) \) | 4.2 \pm 0.8     | 0.051                  |
| South spiral       | 6–10        | \( \leq 0.8 \) | \( (< 20 \, 10^{2.3–4.7} \) cm\(^{-3}\)) \) | ...             | ...                    |

Note. Note that \( R_{0} \) is derived based on an angular resolution of 3\(^{\prime}\) at \( R_{21} \) is 20\(^{\prime}\). The \( I_{\text{HCN}} \) is the single-dish integrated intensity of HCN (1–0) at each position in K km s\(^{-1}\); \( L_{\text{HCN}}/L_{\text{CO}} \) indicates the relative intensity of dense gas and regular gas tracers; \( L_{\text{HCN}}/L_{\text{CO}} \) is computed based on single-dish observations of HCN and \(^{12}\)CO (1–0). The single-dish beam size of these observations is about 20\(^{\prime}\).

Figure 9. Results of LVG calculations with combinations of \( R_{0} \) (dashed curves) and \( R_{21} \) (solid curves) for the defined galactic features in Section 4. In each panel, the gray and black curves represent \( \log(N_{\text{CO}}/d^3) = 16.6 \) and \( 17.3 \) cm\(^{-2}\) (km s\(^{-1}\))\(^{-3}\), respectively. Possible solutions of \( T_{k} \) and \( n_{\text{H}_2} \) are enclosed within the curves of two line ratios and their two \( \log(N_{\text{CO}}/d^3) \) highlighted with gray shadows. (a) Results of the central region where the average \( R_{0} = 17 \) and the average \( R_{21} = 1.0 \). (b) Results of the northern ridge where the average \( R_{0} = 15 \) and the average \( R_{21} = 0.8 \). (c) Results of the southern ridge where the average \( R_{0} = 12 \) and the average \( R_{21} = 0.8 \). (d) Results of the south spiral where the average \( R_{0} = 7 \) and the average \( R_{21} \leq 0.6 \).

Table 2

\( R_{0} (I_{\text{CO}(1\rightarrow 0)/I_{\text{CO}(1\rightarrow 0)}) \) and \( R_{21} (I_{\text{CO}(2\rightarrow 1)/I_{\text{CO}(1\rightarrow 0)}) \) of Each Galactic Structure and the Results of LVG Calculations of Volume Density \( n_{\text{H}_2} \) and Kinetic Temperature \( T_{k} \). Based on the Two Observed Line Ratios

| Region             | \( R_{0} \) | \( R_{21} \) | \( T_{k}, n_{\text{H}_2} \) | \( I_{\text{HCN}} \) | \( L_{\text{HCN}}/L_{\text{CO}} \) |
|--------------------|-------------|-------------|-----------------------------|-----------------|------------------------|
| Central region     | 17          | \( \sim 1.0 \) | \( (\sim 40 \), \( (\sim 10^{3.3} \) cm\(^{-3}\)) \) | 18.9 \pm 1.4     | 0.111                  |
| Northern ridge     | 12–20       | \( \sim 0.8 \) | \( (\sim 20–35 \, 10^{2.3–4.7} \) cm\(^{-3}\)) \) | 4.7 \pm 0.8     | 0.065                  |
| Southern ridge     | 10–13       | \( \sim 0.8 \) | \( (\sim 15–20 \, 10^{2.3–4.7} \) cm\(^{-3}\)) \) | 4.2 \pm 0.8     | 0.051                  |
| South spiral       | 6–10        | \( \leq 0.8 \) | \( (< 20 \, 10^{2.3–4.7} \) cm\(^{-3}\)) \) | ...             | ...                    |

Note. Note that \( R_{0} \) is derived based on an angular resolution of 3\(^{\prime}\) at \( R_{21} \) is 20\(^{\prime}\). The \( I_{\text{HCN}} \) is the single-dish integrated intensity of HCN (1–0) at each position in K km s\(^{-1}\); \( L_{\text{HCN}}/L_{\text{CO}} \) indicates the relative intensity of dense gas and regular gas tracers; \( L_{\text{HCN}}/L_{\text{CO}} \) is computed based on single-dish observations of HCN and \(^{12}\)CO (1–0). The single-dish beam size of these observations is about 20\(^{\prime}\).
Figure 10. (a) Infrared color of $S_{60}/S_{40}$ (flux ratio of 70–160 μm) in contours and color scale. The contours are shown at levels of 0.11, 0.12, 0.13, 0.14, 0.15, 0.17, and 0.20. The black circle indicates the area of central 1′. The cross marks the galactic center. Locations of the northern and southern ridges are marked with symbol × (positions of our HCN observations). A point-spread function of 12″ is indicated at the lower-right corner. (b) A zoom-in view of panel (a). Symbols and color are the same as in panel (a). (c) Infrared color (contours) overlaid on star-forming regions indicated by Spitzer 24 μm (color scale). The levels of the contours are the same as in panel (a). (d) A zoom-in view of panel (c). Symbols and color are the same as in panel (c).

Figure 11. Visualization of the radial range of galactic environments. The $^{12}$CO (1–0) map is shown with gray scale and contours. The galactic center is marked with a cross. The beam size is plotted in the lower-right corner. The annuli (or ellipses) take into account the inclination of 33° and position angle of 243° of the disk. The inner ellipse ($r < 10''$) denotes the unresolved central region. The offset ridges are enclosed within the middle annulus ($10'' < r < 37''$), and spiral arms are enclosed within the outer annulus ($37'' < r < 70''$).

Figure 12. Radial star-formation efficiency ($SFR/M_{\text{BH, 12CO}}$). Dashed, thin solid, and thick solid curves represent the SFE of the northern and southern sides and the average of the two sides, respectively.
7. SUMMARY

In this work, we investigated the physical properties of molecular gas and star-formation activity in the central 2 kpc of NGC 6946. These investigations are done by analyzing the newly observed high-resolution isotopic line $^{13}$CO (1–0) image created by single-dish telescope NRO45 and interferometer CARMA, and other molecular gas tracers in $^{12}$CO (1–0), $^{12}$CO (2–1), and HCN (1–0) (new data from this work), star-formation tracers in H$\alpha$ and 24 $\mu$m, and dust tracers in 60 and 170 $\mu$m from an archive (Section 2). The main observational results of the newly observed molecular gas are as follows (Section 3).

1. The NRO45 and NRO45 + CARMA spectra are very similar overall, while the CARMA spectrum has a flux only about 50% of the NRO45 one.

2. The $^{13}$CO combined map (our default) shows the central component in detail, resolving the central concentration elongated toward the northwest to southeast directions, corresponding to the unresolved nuclear (secondary) bar with a major axis of ~400–500 pc and the circumnuclear starburst ring. The emission appears to extend toward the north from the nuclear bar, reaching the radius of ~1 kpc toward the north. We call this extension the northern ridge (offset ridge of molecular gas of the northern primary bar; Section 4). The emission at the south side is more complex than the north. We define two structures as southern ridge (offset ridge of the southern primary bar) and south spiral, which was misunderstood to be part of the southern bar in previous low-resolution images (Section 4).

3. Comparison to the archival $^{12}$CO map (also a combined map of NRO45 and CARMA) shows that the morphologies of two CO lines are generally similar, but $^{12}$CO emission shows more continuous extension overall than does $^{13}$CO. The $^{12}$CO-to-$^{13}$CO ($R_{10}$) ratio varies by a factor of three from the maximum of ~17 around the galactic center to the minimum of ~6 at the south spiral, covering the large range observed in typical Galactic molecular clouds to starburst galaxies and galaxy mergers.

4. HCN single-dish observations were made toward three selected positions: the central region, the northern ridge, and the southern ridge to constrain the amount of dense gas. The HCN integrated intensities are 18.9 $\pm$ 1.4, 4.7 $\pm$ 0.8, and 4.2 $\pm$ 0.8 K km s$^{-1}$ at the three regions, respectively. A comparison between HCN and CO shows that their overall spectral profiles are similar to each other, except that the spectra at the southern ridge show a slight difference: CO observations show multiple peaks and HCN has only one.

The physical properties of molecular gas are inferred with several methods. The analyses are carried out mainly toward the regions of interest, including the central region, northern ridge, southern ridge, and south spiral (Section 5).

1. The one-zone LVG model and the observed line ratios of $R_{10}$ and $^{12}$CO (2–1)-to-$^{12}$CO (1–0) ($R_{21}$) are used to constrain the spatially resolved temperature and density of the molecular gas. LVG calculations show that the bulk molecular gas traced by CO lines in the galactic center is warmer and denser ($\geq 20–40$ K, $n_{H_2} \geq 10^{3.5}$ cm$^{-3}$) than that in the offset ridges ($\geq 10–20$ K, $n_{H_2} \approx 10^3$–$10^4$ cm$^{-3}$). Moreover, the south spiral likely has a temperature and density lower than that of the ridges.

2. The luminosity ratio of dense gas tracer to low-density gas tracer $L_{H\alpha}^{12}$CO is calculated for the central region and the ridges. The ratio is often referred to as the dense gas fraction. The ratio $L_{H\alpha}^{12}$CO/$L_{H\alpha}^{13}$CO suggests that the fraction of dense gas in the central region is similar to that in starburst galaxies such as LIRGs and ULIRGs, and the values of the ridges are close to the global average values of normal galaxies.

3. A large-scale temperature distribution is calculated by the infrared color of $S_{70\mu m}/S_{60\mu m}$. Temperature is spatially correlated with star-forming regions seen in 24 $\mu$m, suggesting that the large-scale temperature distribution of NGC 6946 is driven by star formation. Moreover, the relative temperatures among the regions of interest inferred from the infrared color are consistent with the results of LVG calculations.

We discuss the variation of radial SFE. The radial SFE in the inner 2 kpc ($\sim 70^\prime$) of NGC 6946 is calculated using the gas traced by $^{12}$CO (1–0) (because it can trace the entire volume within the bulk molecular gas) and star-formation activity traced by 24 $\mu$m and H$\alpha$ (Section 6). The key results are as follows.

1. The SFE of the north side of the galaxy is higher than that of the south side by about two times. For each side of the galaxy, the radial SFE changes by about five times in the inner 2 kpc disk.

2. In spite of the different SFE, the radial SFEs share similar trends of variation at the two sides. A low SFE is seen in the radial range of the inner (midway) offset ridges, whereas the ridge ends show high SFE. The variations of SFE agree with the prediction based on the effect of the dust-lane shocks and the increase in the probability of cloud–cloud collisions in a high-interaction environment.

We thank referees Alessandro Romeo for providing constructive comments that have helped to improve the paper. This work is supported by the Associate Support System of the National Astronomical Observatory of Japan (NAOJ). J.K. acknowledges support from the NSF through grant AST-1211680 for the work presented in this paper, as well as NASA through grant NNX09AF40G & NNX14AF74G, a Herschel - Space Observatory grant, and a Hubble Space Telescope grant (No. 12940). This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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