Nobeyama Millimeter Array Observations of the Nuclear Starburst of M 83: A GMA Scale Correlation between Dense Gas Fraction and Star Formation Efficiency

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Abstract

We present aperture synthesis high-resolution (∼7″ × 3″) observations in CO (J = 1–0), HCN (J = 1–0), and 95 GHz continuum emission toward the central (∼1.5 kpc) region of the nearby barred spiral galaxy M 83 with the Nobeyama Millimeter Array. Our high-resolution CO (J = 1–0) mosaic map depicts the presence of molecular ridges along the leading sides of the stellar bar and a nuclear twin peak structure, whereas the distributions of the HCN (J = 1–0) emission that traces dense molecular gas (n(H2) > a few × 104 cm⁻³) and the 95 GHz continuum emission that traces massive starburst show nuclear single-peak structures. The HCN (J = 1–0) and the 95 GHz continuum peaks are not spatially coincident with the optical starburst regions traced by the HST V-band image, suggesting the existence of deeply buried ongoing starburst due to strong extinction (AV ~ 5 mag) near these peaks. We found that the HCN (J = 1–0)/CO (J = 1–0) intensity ratio, RHCN/CO, correlates well with the extinction-corrected star formation efficiency (SFE) in the central region of M 83 at a resolution of 7″/5 (~160 pc). This suggests that SFE is controlled by a dense gas fraction traced by RHCN/CO, even on a Giant Molecular cloud Association (GMA) scale. Moreover, the correlation between RHCN/CO and SFE in M 83 seems to be almost coincident with that among the Gao and Solomon (2004a, ApJ, 606, 271) sample. This suggests that the correlation between RHCN/CO and the SFE on a GMA (~160 pc) scale found in M 83 is the origin of the global correlation on a few kpc scale shown by Gao and Solomon (2004a).

Key words: galaxies: individual (M 83 = NGC 5236) — galaxies: ISM — galaxies: starburst

1. Introduction

Star formation is one of the most fundamental processes in the evolution of galaxies. Stars are formed by the contraction of the molecular interstellar medium (ISM), and then a new ISM containing heavy elements is dispersed into interstellar space by stellar wind and supernova explosions when stars end their lives. By repeating these processes, ISM, galaxies, and the Universe evolve. Therefore, the physics of star formation is very important for understanding of the evolution of galaxies.

In the central regions of disk galaxies, we often find intense star-formation activities (e.g., Ho et al. 1997), where not only the star formation rate (SFR), but also the star formation efficiency (SFE: Young et al. 1996), which is an intensive parameter defined as the fraction of the SFR surface density in the surface mass density of molecular gas, are also enhanced. These star-formation activities in the central regions of galaxies are different from a simply scaled-up version of that in the disk region, and are referred to as starburst (Kennicutt 1998a). A nuclear starburst is prominent not only because it shows high SFR, but also because it shows elevated SFE. Therefore, for understanding a nuclear starburst we should reveal what causes high SFE star formation.

It is essential to study dense molecular gas, because stars are formed from dense cores of molecular clouds. In fact, recent studies of the dense molecular medium in galaxies are based on observations in the HCN (J = 1–0) emission, a dense molecular gas tracer (n(H2) > a few × 104 cm⁻³) due to its large dipole moment (μHCN = 3.0 Debye, whereas μCO = 0.1 Debye), and demonstrate the intimate connection between dense molecular gas and massive star formation in galaxies. After the pioneer work by Solomon et al. (1992), a tight correlation between the HCN (J = 1–0) intensity and the FIR continuum luminosities has been shown among many galaxies, including nearby ones (Gao & Solomon 2004a, 2004b), and high redshift quasar host galaxies (Carilli et al. 2005; Wu et al. 2005), although some deviations from the correlation are reported toward extreme environments (Riechers et al. 2007; Graciá-Carpio et al. 2008; Kohno et al. 2008a). A spatial coincidence between dense molecular gas traced by the HCN (J = 1–0) emission and massive star-forming regions was also reported (Kohno et al. 1999; Shibatsuka et al. 2003). In addition, Gao and Solomon (2004a) reported that the HCN (J = 1–0)/CO (J = 1–0) integrated intensity ratio in the brightness temperature scale, hereafter RHCN/CO, correlates well with SFE. This suggests that SFE is controlled by the fraction of dense molecular gas to the...
total amount of molecular contents traced by $R_{\text{HCN}/\text{CO}}$ (e.g., Solomon et al. 1992; Kohno et al. 2002; Shibatsuka et al. 2003; Gao & Solomon 2004a).

However, these previous reports on the relationship between the dense gas fraction and SFE are derived from coarse spatial resolution (≥ 30") data of moderately distant galaxies ($D > 10\ Mpc$). This means that the results show a correlation on global scales of galaxies. In our Galaxy, a massive star-forming region is associated with the giant molecular clouds (GMCs) on global scales of galaxies. In our Galaxy, a massive star-forming region is associated with the giant molecular clouds (GMCs) or their associations (giant molecular associations; GMAs). A typical scale of a GMC is a few 10 pc (Scoville & Sanders 1987), and that of a GMA is a few 100 pc. Therefore, we should investigate any correlation between the dense gas fraction and SFE on this scale. To address this issue, observations with high-angular resolution of the central region of nearby galaxies are required.

In this paper, we present CO ($J = 1–0$), HCN ($J = 1–0$), and $95\ GHz$ continuum observations toward the central region of M 83 (NGC 5236) using the Nobeyama Millimeter Array (NMA). M 83 is a nearby, face-on, barred, grand-design spiral galaxy hosting an intense starburst at its center. The distance to M 83 is estimated to be 4.5 Mpc (Thim et al. 2003); therefore, 1" corresponds to 22 pc. We can then discuss the relation between $R_{\text{HCN}/\text{CO}}$ and the SFE at the center of M 83 on a GMA scale with a few arcsec resolution observations, which can be accomplished with the NMA. High-resolution ($\leq 23^\prime \sim 500\ pc$) CO line observations of the central region of M 83 have been performed repeatedly with various telescopes and in various transitions. We summarize them in table 1. For example, Handa et al. (1990) mapped the distribution of CO ($J = 1–0$) emission for the center and the bar at a resolution of 16" using the NRO 45-m telescope. They observed a large concentration of molecular gas in the nucleus and an extended ridge along the major axis of the bar. Ishizuki (1993) reported a CO ($J = 1–0$) observation toward the center with the NMA. The distribution of CO ($J = 1–0$) emission shows a twin-peak structure at the nucleus. Sakamoto et al. (2004) performed CO ($J = 3–2$) and CO ($J = 2–1$) emission observations toward the center and the bar using the Submillimeter Array (SMA). Their CO maps revealed two gas ridges on the leading side of the stellar bar and a nuclear gas ring of ~300 pc in diameter. The distribution of CO ($J = 3–2$) emission is not coincident with the nuclear starburst, which is depicted by a three-color composite image made from HST/WFPC2 data, F300W, F547M, and F814W. The authors mentioned that the

| Transition | Authors          | Telescope | Map size     | Resolution |
|------------|------------------|-----------|--------------|------------|
| $J = 1–0$  | Handa et al. (1990) | NRO 45 m  | 3'5 × 1'     | 16"        |
|            | Ishizuki (1993)   | NMA       | 1'1 × 1'     | 12" × 6"   |
|            | Handa et al. (1994) | NMA      | 1'1 × 1'     | 12" × 6"   |
|            | Kuno et al. (2007) | NRO 45 m  | 6' × 6'      | 16"        |
|            | This work         | NMA       | 2' × 1'      | 7" × 3"    |
| $J = 2–1$  | Wall (1991)       | JCMT 15 m | 22"          |            |
|            | Israel and Baas (2001) | JCMT 15 m | 1'2 × 2'     | 21"        |
|            | Lundgren et al. (2004) | SEST 15 m | 10' × 10'    | 23"        |
|            | Sakamoto et al. (2004) | SMA      | 1'5 × 1'     | 3'8 × 2'5  |
| $J = 3–2$  | Wall (1991)       | CSO 10 m  | 22"          |            |
|            | Petitpas and Wilson (1998) | JCMT 15 m | 0'7 × 0'7    | 14"        |
|            | Israel and Baas (2001) | JCMT 15 m | 1'2 × 1'7    | 14"        |
|            | Dumke et al. (2001) | SMTO 10 m | 2' × 2'      | 22"        |
|            | Sakamoto et al. (2004) | SMA      | 0'6 × 0'6    | 3'1 × 1'5  |
|            | Bayet et al. (2006) | CSO 10 m  | 4'5 × 2'     | 22"        |
|            | Muraoka et al. (2007) | ASTE 10 m | 5' × 5'      | 22"        |
| $J = 4–3$  | Petitpas and Wilson (1998) | JCMT 15 m | 0'6 × 0'5    | 11"        |
|            | Israel and Baas (2001) | JCMT 15 m | 0'5 × 0'5    | 11"        |

Table 1. Previous high-resolution CO observations of M 83.
nuclear starburst in M 83 is lopsided, mostly on the receding side (south) of the dynamical center. It is difficult to estimate the star-formation activity accurately in the central starburst region because of strong extinction. Harris et al. (2001) presented a photometric catalog of 45 massive star clusters in the nuclear starburst region of M 83, observed with HST/WFPC2. They revealed that the ages of star clusters in the central 300 pc are younger than 10 Myr old, and the cluster age distribution has an extremely sharp peak at 5–7 Myr. However, the cluster ages in the north side of the nucleus are unknown, since no clusters were found due to strong extinction by dust. They also mentioned the original starburst had started at the southern end of the nuclear starburst region, and propagated northward. The propagation of star formation is also reported by Ryder et al. (2005) and by Houghton and Thatte (2008), who could quantify the age of star formation in the central region of M 83.

The goals of this paper are: (1) to obtain distributions of the total molecular gas and dense molecular gas through \( \text{CO} (J = 1–0) \) line, and \( \text{HCN} (J = 1–0) \) line emission in the central 1.5 kpc region of M 83 with a spatial resolution of \( \sim 100 \) pc, (2) to evaluate the extinction and reveal its distribution, and to obtain the extinction-corrected SFR and SFE, and (3) to examine the correlation between dense gas fraction traced by \( R_{\text{HCN/CO}} \) and the SFE on a GMA scale.

2. Observations and Data Reduction

Aperture synthesis observations in the \( \text{CO} (J = 1–0) \) line, the \( \text{HCN} (J = 1–0) \) line, and the 95 GHz continuum emission towards the central region (\( \sim 1.5 \) kpc) of M 83 were carried out with the NMA during periods from 2003 December to 2004 April, and from 2005 December to 2006 April. \( \text{CO} (J = 1–0) \) line observations were made toward 3 adjacent field-of-views (FOVs) to make a mosaic of the center of the galaxy. \( \text{HCN} (J = 1–0) \) line and 95 GHz continuum observations were made toward only a central FOV. Figure 1 shows each FOV superposed on a \( V \)-band image obtained with the VLT (Comerón 2001).

The NMA consists of six 10-m antennas equipped with cryogenically cooled receivers employing Superconductor-Insulator-Superconductor mixers in double side band operation. Three antenna configurations (AB, C, and D) were used during the observations. The backend used was the Ultra Wide-Band Correlator (Okumura et al. 2000).

### Table 2. Observation parameters and results of M 83 with the NMA.

| Observed line | \( \text{CO} (J = 1–0) \) | \( \text{HCN} (J = 1–0) \) |
|--------------|-------------------------|---------------------------|
| Rest frequency | [GHz] | 115.271204 | 88.631604 |
| Band width | [MHz] | 512 | 1024 |
| Band resolution | [MHz] | 2 | 8 |
| Velocity resolution | [\( \text{km s}^{-1} \)] | 5.2 | 27.1 |
| Sideband | | upper | lower |
| FOV | [''] | 59 | 77 |
| Number of FOVs | | 3 (mosaic) | 1 |
| Observed date | | 2003/12–2004/4 | 2005/12–2006/4 |
| Synthesized beam size | [''] | 7.2 \( \times \) 3.4 | 7.1 \( \times \) 3.1 |
| Equivalent \( T_b \) | [K (\( \text{Jy beam}^{-1} \))\(^{-1} \)] | 3.76 | 7.15 |
| rms noise (channel map) | [mJy beam\(^{-1} \)] | 85 | 7.2 |
| rms noise (intensity map) | [mK] | 320 | 51.5 |
| Total flux within FOV | [Jy km s\(^{-1} \)] | 2.7 | 0.52 |
| | [K km s\(^{-1} \)] | 10.2 | 3.72 |

The central position of the FOV:
- Right ascension (J2000.0): 13\( ^h \)37\( ^m \)00.90
- Declination (J2000.0): \(-29^\circ 51' 56'' 7''\)

* Reference of the central position of the FOV — Jarrett et al. (2003).

### Table 3. Summary of the 95 GHz continuum in M 83.

| Synthesized beam | Equivalent \( T_b \) | rms noise |
|------------------|-----------------|-----------|
| [''] | [K (\( \text{Jy beam}^{-1} \))\(^{-1} \)] | [mJy beam\(^{-1} \)] |
| | | [mK] |
| | | Total flux within FOV [mJy] |

* Here, 95 GHz means a combination of 88.741 \( \pm \) 0.5 GHz and 100.741 \( \pm \) 0.5 GHz.
Fig. 2. (top left) Integrated intensity map in the CO ($J = 1-0$) emission in the central region of M 83. The central cross indicates the dynamical center determined from our CO velocity field, and dashed white circles indicate the FOVs of CO ($J = 1-0$) observations. The synthesized beam is shown in the lower left corner. The contour levels are 3, 6, 9, 12, 15, 21, 27, and 33 K km s$^{-1}$, where $1 K km s^{-1} = 2.7 Jy beam^{-1}$ km s$^{-1}$ or 10 K km s$^{-1}$. (top right) Velocity field measured in CO ($J = 1-0$). The contour levels are from 440 to 590 km s$^{-1}$ with an interval of 10 km s$^{-1}$. (bottom left) Integrated intensity map in the HCN ($J = 1-0$) emission in the central region of M 83. The contour levels are 3, 6, 9, 12, and 15 K km s$^{-1}$, where $1 K km s^{-1} = 0.52 Jy beam^{-1}$ km s$^{-1}$ or 3.7 K km s$^{-1}$. (bottom right) Map of the 95 GHz continuum emission in the central region of M 83. The contour levels are 2, 4, 6, 8, and 10 K km s$^{-1}$, where $1 K km s^{-1} = 0.85 mJy beam^{-1}$ or 4.3 mK.

A radio source, J1337−129, was observed every ~20 min for amplitude and phase calibrations, and the passband shape of the system was determined from observations of a strong continuum source, 3C 273. The flux density of J1337−129 was measured at several times during an observing run based on that of a quasar, 3C 345. Its flux was determined by flux measurements of Saturn and Uranus. The overall error of the absolute flux scale was estimated to be about ±20%.

The raw visibilities were edited and calibrated using the NRO UVPROC-II package (Tsutsui et al. 1997), and then final images were created using the IMAGR task in the NRAO AIPS package. For some spectral line analysis, data also have continuum emission. In this case, we subtracted the continuum emission from the visibilities using the UVPROC-II task LCONT at first. We used the subtracted continuum emission in HCN ($J = 1-0$) data as the 95 GHz continuum
Table 4. Peaks/nuclei in the central region of M 83.

| RA (J2000) | Dec (J2000) | Description | Reference |
|------------|-------------|-------------|-----------|
| 13 37 00.90 | -29 51 56.70 | 2MASS, (the central position of the FOV) | Jarrett et al. (2003) |
| 13 37 00.73 | -29 51 57.90 | dynamical center determined from CO velocity field | This work |
| 13 37 00.38 | -29 51 53.50 | 95 GHz continuum peak | This work |
| 13 37 00.52 | -29 51 53.50 | peak of extinction-corrected Hα luminosity | This work |
| 13 37 00.95 | -29 51 55.50 | K-band photometric peak, visible nucleus | Thatte et al. (2000) |
| 13 37 00.57 | -29 51 56.90 | the symmetry center of the outer K-band isophotes | Thatte et al. (2000) |
| 13 37 00.46 | -29 51 53.60 | hidden mass concentration | Díaz et al. (2006) |

Fig. 3. Several peaks/nuclei in the central region of M 83 superposed on the HCN ($J = 1–0$) integrated intensity map. The contour levels are the same as those at the bottom left of figure 2. The open circle shows an infrared peak identified by the 2MASS image (the central position of the FOV), the filled circle shows the dynamical center, the open square shows the 95 GHz continuum peak, the filled square shows the peak of extinction-corrected Hα luminosity (see subsection 4.1), the open triangle shows the visible nucleus, the filled triangle shows the symmetry center of the outer K-band isophotes, and the x mark shows the hidden mass concentration. See table 4 and text for details.

Fig. 4. CO ($J = 1–0$) spectra at the center of M 83. The thick line corresponds to the spectrum obtained with the NRO 45-m (Kuno et al. 2007), and the thin line corresponds to that with the NMA (this work), which is convolved to the resolution of 16'' to match the NRO 45-m data. The velocity resolutions of these spectra are both 5.2 km s$^{-1}$. The spectrum obtained with the NMA does not have a single peak, but a twin-peak profile, and its intensity is ~30% lower than that obtained with the NRO 45-m.

3. Results

3.1. Maps

Figure 2 shows an integrated intensity map and a velocity field in the CO ($J = 1–0$) line, an integrated intensity map in the HCN ($J = 1–0$) line, and a map of the 95 GHz continuum emission. Our high-resolution CO ($J = 1–0$) mosaic map depicts the presence of molecular ridges along the leading sides of the stellar bar and nuclear twin-peaks structure. This structure was also seen in previous studies in the CO ($J = 1–0$) (Handa et al. 1994), and in the CO ($J = 2–1$) and the CO ($J = 3–2$) (Sakamoto et al. 2004). Strong non-circular motion along the molecular ridges was also detected in the velocity field. This strong non-circular motion is well consistent to that detected in the CO ($J = 2–1$) velocity field (Sakamoto et al. 2004). The motion might play an important role in feeding large amounts of molecular gas into the starburst nucleus. We determined the dynamical center from the CO velocity field using the AIPS task GAL (see table 4). We have found that the distributions of the HCN ($J = 1–0$) line intensity, and the 95 GHz continuum flux are confined to a single peak, corresponding to the northern peak seen in the CO map. This means that dense molecular gas traced by the HCN ($J = 1–0$) line and current star formation traced by the 95 GHz continuum emission are distributed only at the north side of the center, although
less dense molecular gas seen in the CO \((J = 1–0)\) line emission is widely distributed in the central region. The peak position of the HCN \((J = 1–0)\) line intensity is consistent spatially with the youngest star clusters found by Harris et al. (2001) and Houghton and Thatte (2008).

Here, we summarize the positions of several peaks and nuclei determined from near-IR and our mm-wave data in figure 3 and table 4. The dynamical center determined from our CO velocity field is near to the symmetry center of the outer \(K\)-band isophotes, whereas the visible nucleus (that is also the location of the \(K\)-band photometric peak in table 4) is offset from the dynamical center and the peaks of the HCN \((J = 1–0)\) line intensity, 95 GHz continuum emission, and the extinction-corrected H\(\alpha\) luminosity (see subsection 4.1). The position of the hidden mass concentration discussed in Díaz et al. (2006) and Houghton and Thatte (2008) seems to be coincident with the peaks of the HCN \((J = 1–0)\) line intensity and the 95 GHz continuum emission, although the spatial resolutions of our mm-wave data \((7'' \times 3'')\) are insufficient to make a detailed comparison.

We compare our HCN \((J = 1–0)\) map with that obtained by Helfer and Blitz (1997). The peak positions of the HCN \((J = 1–0)\) line emission are almost coincident between these two maps, whereas the flux values of the peak position are different. When our map was convolved to \(12'\times 4'\), which is the beam size of their map, the peak flux was measured as 12.5 Jy km s\(^{-1}\). This value is about 30% lower than that of their data. It is unclear what causes such a significant discrepancy. Note that our HCN \((J = 1–0)\) line flux measured with the NMA is well consistent with that measured with the NRO 45-m telescope for the central 22\(''\) region (see subsection 3.2).

3.2. Combining CO \((J = 1–0)\) Data Obtained with the NMA and the NRO 45-m

We found that the CO \((J = 1–0)\) spectrum at the center of M 83 obtained with the NMA is different from that obtained...
with the NRO 45-m telescope (Kuno et al. 2007) at the same resolution of 16", as shown in figure 4. This corresponds to missing flux of the interferometry, and we evaluated that the missing flux was ~30%. In order to correct for the missing flux and obtain the true flux value in the CO ($J = 1$–$0$) emission with the NMA, we combined the NMA CO ($J = 1$–$0$) data with the NRO 45-m CO ($J = 1$–$0$) data.

We employed the latest CO ($J = 1$–$0$) data (M. Fukuhara et al. 2009, in preparation) obtained with the NRO 45-m using the On-the-Fly (OTF) method. The combining of two CO ($J = 1$–$0$) data sets was performed using MIRIAD. Figure 5 shows a combined CO ($J = 1$–$0$) image and an CO ($J = 1$–$0$) image only with the NMA data. The results and specifications of the combining are summarized in table 5. Compared to the NMA-only image, the flux was properly recovered at the center, and the CO-emitting area is enlarged in the combined image. That is, emission from diffuse components of the molecular gas could be reproduced appropriately. The 45-m data made the resultant noise level lower and the synthesized beam size slightly wider. However, the overall structure at the center, such as the twin-peaks (or ring-like) was only slightly affected by this combining process. For the CO ($J = 1$–$0$) line, we did not combine the NMA data with the single-dish data. This is because we could not find any missing flux in the HCN ($J = 1$–$0$) flux for the central 22" region. The flux obtained with the NMA, $38 \pm 3$ Jy km s$^{-1}$, coincides well with that obtained with the NRO 45-m, $39 \pm 2$ Jy km s$^{-1}$ (A. Hirota et al. 2009, private communication). This means that there is no significant diffuse component of HCN ($J = 1$–$0$) emission. The difference in missing flux between CO ($J = 1$–$0$) flux and HCN ($J = 1$–$0$) flux suggests that the HCN emitting region is more restricted than the CO emitting region. This is because HCN ($J = 1$–$0$) emission originates from dense molecular gas ($n_{\text{H}_2} > 10^4$ cm$^{-3}$) associated with the star-forming region, whereas the CO ($J = 1$–$0$) emission originates from the low-dense ($n_{\text{H}_2} \sim 10^2$ cm$^{-3}$) component of molecular gas, which is distributed ubiquitously.

We compare the combined CO ($J = 1$–$0$) image with the NMA HCN ($J = 1$–$0$) image in figure 6. This corresponds to a comparison between the total amount of the molecular gas and the dense molecular gas which will host star-formation activity soon. The peak of the HCN ($J = 1$–$0$) intensity is almost coincident with the northern peak of CO ($J = 1$–$0$) intensity, whereas little HCN ($J = 1$–$0$) emission was seen at the southern peak of CO ($J = 1$–$0$). The smaller fraction of the dense gas at the southern peak suggests that this region may be in a post-star-formation phase.

### 3.3. HCN ($J = 1$–$0$)/CO ($J = 1$–$0$) Intensity Ratio $R_{\text{HCN}/\text{CO}}$

We made an intensity ratio map from the HCN ($J = 1$–$0$) data and the combined CO ($J = 1$–$0$) data. In order to improve the data quality and to adjust the beam size, we convolved the images to have the same $7.5 \times 7.5$ (160 pc x 160 pc) resolution before calculating the ratio. The resultant $R_{\text{HCN}/\text{CO}}$ map is shown in figure 7. The peak of $R_{\text{HCN}/\text{CO}}$ value is $0.11 \pm 0.01$. The region with high $R_{\text{HCN}/\text{CO}}$ is concentrated to the north side of the dynamical center of the galaxy. The high ratio region has an elongation southward toward the dynamical center.
3.4. Comparison with Optical Image

To compare our millimeter-wave images with an optical image obtained with the HST/WFPC2, we made maps of the combined CO ($J = 1–0$) intensity, the HCN ($J = 1–0$) intensity, the 95 GHz continuum, and $R_{\text{HCN/CO}}$, respectively, superposed on the HST $V$-band image (F547M) obtained from HST/WFPC2 archival data. These maps are shown in figure 8. The $V$-band image shows the distribution of optically luminous young star clusters, which is referred to as “optical starburst.” The optical starburst region is distributed on the south side of the center, and is confined between the twin peaks in the CO ($J = 1–0$) emission line. The distribution of the HCN ($J = 1–0$) integrated intensity is shifted northward with respect to that of the optical starburst. Moreover, even the 95 GHz continuum, which is believed to trace the current star formation as well as Hα, is also clearly shifted northward from the optical starburst region, and the peak is close to that in the HCN ($J = 1–0$) line. This means that the “optical starburst” seen in the $V$-band does not trace the current star-forming region. This fact is also reported on the basis of near-IR imaging (Ryder et al. 2005; Houghton & Thatte 2008).

Fig. 8. (top left) Integrated intensity map of the combined CO ($J = 1–0$) (contour) superposed on the HST V-band (F547M) image (gray scale). The contour levels are the same as those in the right of figure 5. The central cross indicates the dynamical center. (top right) Integrated intensity map in the HCN ($J = 1–0$) (contour) superposed on the HST V-band image (gray scale). The contour levels are the same as those in the bottom left of figure 2. (bottom left) 95 GHz continuum image (contour) superposed on the HST V-band image (gray scale). The contour levels are the same as those in the bottom right of figure 2. (bottom right) $R_{\text{HCN/CO}}$ map (contour) superposed on the HST V-band image (gray scale). The contour levels are the same as those in figure 7.
4. Discussion

4.1. Extinction in the Central Region of M 83

As described in the previous section, we found that the optical starburst region of M 83 is not spatially coincident with the current star-forming region traced by the 95 GHz continuum. This spatial inconsistency is probably due to strong extinction. To confirm this possibility, we estimated the magnitude and distribution of the extinction.

Some previous studies conclude that extinction at the center of M 83 is not small. Thatte et al. (2000) reported that the V-band extinction, $A_V$, spreads from 0.5 to 9.2 mag in the central 12′ (~250 pc) region. Harris et al. (2001) reported that extinction to the north of the center (~15′ or 330 pc) is stronger than that to the south. This suggests that $A_V$ is different from place to place, and it is very large. Therefore,
we should estimate the $A_V$ with sufficient accuracy.

To estimate the Hα extinction, $A_{Hα}$, we used the Paα emission. We employed an Hα image obtained with the CTIO 1.5-m telescope (Meurer et al. 2006) and a Paα image obtained with archival data of the HST/NICMOS camera (P.I. M. Rieke, Proposal I.D. 7218). The Paα image was convolved to be the same resolution as that of the Hα, 1″84, although the resolution of the Paα image is 0″15. Note that the FOV of the Paα image is narrower than that of NMA observations.

We adopted a metallicity-dependent intrinsic ratio of Hα/Paα = 8.45 based on the assumption of an electron temperature of $T_e = 10000$ K for $n_e = 100$ cm$^{-3}$ (Osterbrock & Ferland 2006). This means that without any extinction

$$L_{Hα,corn}/L_{Paα,corr} = 8.45,$$

(1)

where $L_{Hα,corn}$ means extinction-corrected Hα luminosity, and $L_{Paα,corr}$ means that of Paα. From the extinction curve we used

$$A_{Hα}/A_{Paα} = 6.0.$$  

(2)

By combining these two relations, we obtained a formula to calculate $A_{Hα}$:

$$L_{Hα,corn}/L_{Paα,corr} = \left(10^{4A_{Hα}/2.5L_{Hα,obs}}\right)/\left(10^{4A_{Paα}/2.5L_{Paα,obs}}\right)\times 8.45.$$  

(3)

Since $L_{Hα,obs}$ and $L_{Paα,obs}$ can be calculated from each observed set of data, $A_{Hα}$ could be obtained.

Figure 9 shows the obtained $A_{Hα}$ map and an extinction-corrected Hα luminosity map for the central 20″ region of M 83. The maximum $A_{Hα}$ is about 4 mag, and its location is almost coincident with the nuclear peak of the HCN ($J = 1–0$) emission. $A_{Hα} \sim 4$ mag corresponds to $A_V \sim 5$ mag. Thus, the optical light is extinct by a factor of 100 around the HCN ($J = 1–0$) peak. In addition, the peak of the extinction-corrected Hα luminosity coincides well with those of the $A_{Hα}$ and the CO ($J = 1–0$) line, the HCN ($J = 1–0$) line, and the 95 GHz continuum emission. On the other hand, the extinction is almost negligible to the south of the center. This inhomogeneous extinction shows why the optical starburst is clearly visible to the south of the center, but almost invisible on the north side. This suggests the existence of deeply buried ongoing starburst with strong extinction, which has already been reported by several authors (e.g., Ryder et al. 2005; Houghton & Thatte 2008), near the peaks in the HCN ($J = 1–0$) line and the 95 GHz continuum emission.

4.2. Star Formation Rates at the Center of M 83

In order to discuss the relationship between dense molecular gas and star formation, we estimated the SFR in the central 22″ (≈500 pc) region of M 83. We used various SFR indicators, i.e., our 95 GHz (3 mm) continuum emission, 5 GHz (6 cm) continuum emission, infrared (IR) luminosity, and extinction-corrected Hα luminosity. All of them should be consistent when all corrections are applied properly.

4.2.1. SFR derived from thermal free–free emission flux

Continuum emission at 95 GHz is expected to be an extinction-free tracer of SFR. This is because the continuum emission at this wavelength is dominated by thermal free–free emission, and is therefore directly converted to the Lyman photon rate (Condon 1992).

By assuming that the observed 95 GHz continuum is dominated by the thermal free–free emission, a Lyman continuum rate or Hα luminosity can be evaluated by the following formula (Condon 1992; Kohno et al. 2008b):

$$L_{Hα} = 9.6 \times 10^{17} \frac{D}{\text{Mpc}} \left(\frac{T_e}{10^4 \text{K}}\right) \left(\frac{\nu}{\text{GHz}}\right)^{0.1} \times \left(\frac{S_{\text{thermal}}}{\text{mJy}}\right) \text{erg s}^{-1},$$

(4)

where $D$ is the distance to the galaxy, $T_e$ is the electron temperature, $\nu$ is the frequency, and $S_{\text{thermal}}$ is the flux density of the thermal free–free continuum emission. We assumed that the observed 95 GHz continuum flux within the central 22″ region of M 83, $S_{\text{thermal}} = 30$ mJy, is dominated by the thermal free–free continuum emission. Then, we derived $L_{Hα}(95 \text{GHz}) = 9.2 \times 10^{40} \text{erg s}^{-1}$. Using this $L_{Hα}(95 \text{GHz})$, we could derive an SFR by adopting the relation between Hα luminosity and SFR (Kennicutt 1998a, Kennicutt 1998b),

$$\text{SFR} = 7.9 \times 10^{-42} \frac{L_{Hα}}{\text{erg s}^{-1}} \frac{M_\odot}{\text{yr}^{-1}}.$$  

(5)

The resultant SFR from our 95 GHz continuum flux is $0.73 \pm 0.21 M_\odot \text{yr}^{-1}$. The error was estimated from the signal-to-noise (S/N) ratio of the 95 GHz continuum map.

4.2.2. SFRs derived from IR luminosity and non-thermal radio continuum flux

In order to evaluate the validity of the derived SFR from 95 GHz continuum flux, we computed the SFR from the IR luminosity and the 5 GHz radio continuum flux. According to Kennicutt (1998b), the SFR derived from the IR luminosity within the central 22″ region is $0.37 M_\odot \text{yr}^{-1}$, which is almost half the value of the SFR based on the 95 GHz continuum.

We then derived the SFR from the 5 GHz radio continuum flux. The non-thermal radio luminosity is related to the observed radio continuum flux density as

$$L_{\text{non–thermal}} = 1.2 \times 10^{17} \frac{D}{\text{Mpc}} \left(\frac{S}{\text{mJy}}\right) \times \left\{1 - \left[1 + 10 \left(\frac{\nu}{\text{GHz}}\right)^{0.1-\alpha}\right]^{-1}\right\} \text{W Hz}^{-1},$$

(6)

(Kohno et al. 2008b), where $D$ is the distance, $S$ the observed flux density at a frequency of $\nu$, and $\alpha$ the non-thermal continuum spectral index (≈0.8). This non-thermal radio luminosity is related to an SFR as

$$\text{SFR} = 8.2 \times 10^{-22} \left(\frac{\nu}{\text{GHz}}\right)^{\alpha} \left(\frac{L_{\text{non–thermal}}}{\text{W Hz}^{-1}}\right) \frac{M_\odot}{\text{yr}^{-1}}.$$  

(7)

(Jogee et al. 2005). From these equations and a 5 GHz radio continuum map produced by Neininger et al. (1993), we obtained an SFR of $0.73 \pm 0.15 M_\odot \text{yr}^{-1}$ within the central 22″ region, which is the same value as the SFR based on the 95 GHz continuum.
4.2.3. SFR derived from extinction-corrected Hα luminosity

SFR can be calculated from the Hα luminosity, as shown in equation (5). However, the Hα emission often suffers from extinction by interstellar dust. In fact, there is up to 4 mag of Hα extinction in the central region of M 83, as described in the previous subsection.

Therefore, there is no doubt that an appropriate correction of the extinction is indispensable. Here, we must verify what data should be used to correct the extinction. Paer seems to be very useful, but cannot cover the entire FOV of the CO (J = 1–0) and HCN (J = 1–0) image.

Recently, the Spitzer/MIPS 24 μm image has begun to be employed for calibrating SFR (e.g., M 51: Calzetti et al. 2007). An archival MIPS 24 μm image (P00059, George, Rieke, Starburst activity in nearby galaxies) covers the entire disk of M 83, and the spatial resolution of the image is about 5′.7. The formula used to calibrate the Hα luminosity using the 24 μm image is as follows (Calzetti et al. 2007):

\[ L_{\text{Hα,corr}} = L_{\text{Hα,obs}} + (0.031 ± 0.006) L_{24\mu m}, \text{ erg s}^{-1}, \]  

(8)

where \( L_{\text{Hα,obs}} \) means the observed Hα luminosity, and \( L_{24\mu m} \) means that of 24 μm. At the center of M 83, the Hα extinction derived from the MIPS 24 μm image is about 3 mag at a resolution of 5′.7. Considering the difference in the spatial resolution, the derived Hα extinction from MIPS 24 μm image seems to be consistent with that from the Paer image. Using equation (5), the resultant SFR from the extinction-corrected Hα is 0.24 ± 0.05 \( M_\odot \text{yr}^{-1} \) within the central 22′ region. This value is close to that from IR luminosity, but 3-times smaller than that from the 95 GHz and 5 GHz continuum flux.

The SFR values derived from various indicators are summarized in table 6. It is unclear what causes such a significant discrepancy among these SFRs.

4.3. Comparison between \( R_{\text{HCN/CO}} \) and SFE

4.3.1. Derivation of SFE

In order to compare the SFE in the central region directly with our \( R_{\text{HCN/CO}} \) data, we need reliable SFR data with an adequate sensitivity and an adequate spatial resolution higher than 7′.5. For the IR luminosity data and the 5 GHz continuum data, their spatial resolutions (≥10′) are inadequate. In addition, our 95 GHz continuum data is unfavorable for comparing \( R_{\text{HCN/CO}} \), since the area where 95 GHz continuum emission is detected in adequate S/N ratio (more than 5σ) is narrower than that of \( R_{\text{HCN/CO}} \). We then used the SFR data based on the extinction-corrected Hα luminosity using MIPS 24 μm data in order to calculate the SFE in the central region.

The SFE is calculated as follows:

\[ \text{SFE} = \left( \frac{\Sigma_{\text{SFR}}}{M_\odot \text{yr}^{-1} \text{pc}^{-2}} \right) \left( \frac{\Sigma_{H_2}}{M_\odot \text{pc}^{-2}} \right)^{-1} \text{yr}^{-1}. \]  

(9)

\( \Sigma_{\text{SFR}} \) is the surface mass density of SFR, and \( \Sigma_{H_2} \) is that of molecular gas. \( \Sigma_{H_2} \) is calculated as follows:

\[ \Sigma_{H_2} = 2.89 \cos i \left( \frac{I_{\text{CO}(J=1-0)}}{K \text{ m s}^{-1}} \right) M_\odot \text{pc}^{-2}, \]  

(10)

where \( i \) is the inclination of this galaxy, 24°. Here, the \( N_{H_2}/I_{\text{CO}} \) conversion factor (\( \chi_{\text{CO}} \)) is assumed to be 1.8 \( \times 10^{20} \text{ cm}^{-2} (\text{K m s}^{-1})^{-1} \) (Dame et al. 2001). \( I_{\text{CO}(J=1-0)} \) was derived from the combined CO (J = 1–0) intensity map. Figure 10 shows the calibrated \( \Sigma_{\text{SFR}} \) map and the SFE map. Both maps were convolved to a resolution of 7′.5 × 7′.5 (160 pc × 160 pc) to match the \( R_{\text{HCN/CO}} \) data. The peak value of the SFR is \( \sim 4 \times 10^{-6} M_\odot \text{yr}^{-1} \). The peak value of SFE (i.e., the site where most active star formation is supposed to occur) is \( \sim 5 \times 10^{-3} \text{yr}^{-1} \) and it is located north of the center. The highest SFE region is spatially coincident well with the highest SFR region.

4.3.2. \( R_{\text{HCN/CO}} \) vs. SFE in M 83: correlation in a GMA scale

Here, we compare \( R_{\text{HCN/CO}} \) with the SFE within the central 1 kpc region of M 83. Figure 11 shows a map of \( R_{\text{HCN/CO}} \) superposed on that of SFE. The spatial correlation between these two maps seems to be fairly good, but \( R_{\text{HCN/CO}} \) map seems to trail the skirt toward the northeast. This skirt-like structure of \( R_{\text{HCN/CO}} \) is not seen in the SFE map, and is coincident with the dust lane seen in the VLT V-band image (Comerón 2001).

In addition, we examined the correlation between \( R_{\text{HCN/CO}} \) and the SFE. For the region where \( R_{\text{HCN/CO}} \) exceeds 0.02, the values of \( R_{\text{HCN/CO}} \) and the SFE were obtained for each separation of 3′.75, which corresponds to half of the spatial resolution of each map. Figure 12 shows a plot of \( R_{\text{HCN/CO}} \) vs. the SFE in each region. The correlation between \( R_{\text{HCN/CO}} \) and the SFE is clearly seen.

These \( R_{\text{HCN/CO}} \) correspond to the dense gas fraction in the central region of M 83 on a 160 pc (corresponding to GMA) scale. The dense gas fraction would be translated as the number of star-forming dense cores per unit gas mass. Then, the correlation derived between \( R_{\text{HCN/CO}} \) means that an outbreak of extensive star formation (high-SFE star formation), such as the nuclear starburst, requires the generation of a large number of star-forming dense cores within GMAs (e.g., Solomon et al. 1992; Kohno et al. 2002; Shibatsuka et al. 2003; Gao & Solomon 2004a).

4.3.3. \( R_{\text{HCN/CO}} \) vs. SFE: comparison with a global scale correlation

We compared our results with that shown by Gao and Solomon (2004a). We converted the SFR in M 83, which was estimated from extinction-corrected Hα luminosity, to the total IR (8 to 1000 μm) luminosity using the following formula (Kennicutt 1998b):

\[ L_{\text{IR}} = 2.2 \times 10^{43} \left( \frac{\text{SFR}}{M_\odot \text{yr}^{-1}} \right) \text{ erg s}^{-1}. \]  

(11)

We then adapted the vertical axis of our \( R_{\text{HCN/CO}} \) vs. SFE plot to that of figure 5a in Gao and Solomon (2004a). Figure 13
Fig. 10. (left) A map of the SFR in the central region of M 83 estimated from calibrated Hβ luminosity. The central cross indicates the dynamical center. The peak of the SFR is $4 \times 10^{-6} M_\odot \text{yr}^{-1} \text{pc}^{-2}$. The spatial resolution of this map is $7.5 \times 7.5$, indicated by a circle in the left corner. (right) A map of the SFE in the central region of M 83. The peak of the SFE is $5 \times 10^{-9} \text{yr}^{-1}$, and it coincides well spatially with that of SFR.

Fig. 11. A map of $R_{\text{HCN/CO}}$ (white contour) superposed on a map of the SFE (color) in the central region of M 83. The central cross indicates the dynamical center. The spatial correlation between these two maps seems to be fairly good. The contour levels are the same as those of figure 7.

shows a composite of the $R_{\text{HCN/CO}}$ vs. SFE plot for the center of M 83 and for ultra luminous infrared galaxies (ULIRGs), luminous infrared galaxies (LIRGs), and normal spirals (Gao & Solomon 2004a). The correlation between $R_{\text{HCN/CO}}$ and the SFE in the central region of M 83 almost seems to coincide with that of Gao and Solomon (2004a) sample. This suggests that the correlation between $R_{\text{HCN/CO}}$ and SFE on a GMA ($\sim 160 \text{pc}$) scale found in the nuclear starburst region of M 83 is the origin of the global correlation on a galactic (a few kpc) scale shown by Gao and Solomon (2004a). In other words, $R_{\text{HCN/CO}}$ (dense gas fraction) and SFE on a galactic scale are averages of those parameters on a GMA scale. Low-$R_{\text{HCN/CO}}$ (less dense) GMAs would be dominant in a low-SFE galaxy, whereas high-$R_{\text{HCN/CO}}$ (dense) GMAs are possibly dominant in a high-SFE galaxy. This is consistent with the prediction of a three-dimensional, high-resolution hydrodynamic simulation

Fig. 12. Plot of $R_{\text{HCN/CO}}$ vs. SFE in the central region of M 83. The correlation between $R_{\text{HCN/CO}}$ and the SFE is clearly seen in $7.5 \times 7.5$ (160 pc $\times$ 160 pc) scale.
5. Summary

We performed aperture synthesis high-resolution (≈ 7″ × 3″) observations in the CO (J = 1–0) line, the HCN (J = 1–0) line, and the 95 GHz continuum emission toward the central region (≈ 1.5 kpc) of the nearby barred spiral galaxy M 83 with the NRAO. A summary of this work is as follows:

1. The size of the CO (J = 1–0) map is 2′ × 1′ (3 pointings mosaic observations). The synthesized beam size and the resultant rms noise level of the intensity map are 7″ × 3″ and 2.7 Jy beam−1 km s−1, respectively. Our high resolution CO (J = 1–0) mosaic map with the highest sensitivity and the highest spatial resolution to date depicts the presence of molecular ridges along the leading sides of the stellar bar and nuclear twin peak structure. In addition, we combined the NRAO CO (J = 1–0) data with the NRO 45-m CO (J = 1–0) data. The combined CO (J = 1–0) map first reveals the high-resolution distribution of molecular gas containing diffuse components in the central region of M 83.

2. The size of the HCN (J = 1–0) map and the 95 GHz continuum map is 77″. The synthesized beam size is 7″ × 3″ for the HCN (J = 1–0) map and 8″ × 3″ for the 95 GHz continuum map, respectively. The resultant noise level is 0.52 Jy beam−1 km s−1 for the HCN (J = 1–0) intensity map and 0.85 mJy beam−1 for 95 GHz continuum map, respectively. We found the distribution of the HCN (J = 1–0) line emission, which traces dense molecular gas, shows a nuclear single peak structure, and coincides well with that of the 95 GHz continuum emission, which traces massive starburst. However, the peaks of the HCN (J = 1–0) line and the 95 GHz continuum emission are not associated with the optical starburst traced by the HST V-band image.

3. Using the Hα/PAH ratio, an extinction map of the center of M 83 was obtained. The highest extinction is A_Hα ≈ 4 mag (A_V ≈ 5 mag), and which spatially coincides with the peak of the extinction-corrected Hα luminosity and that of the HCN (J = 1–0) line emission. This suggests the existence of deeply buried ongoing starburst due to strong extinction near the peaks of the HCN (J = 1–0) line and the 95 GHz continuum emission.

4. We found that R_{HCN/CO} correlates well with the extinction-corrected SFE using the MIPS 24 μm data in the central region of M 83 at a resolution of 7″.5 (≈ 160 pc). That is, the SFE is controlled by dense gas fraction traced by R_{HCN/CO} on a GMA scale. In addition, the correlation between R_{HCN/CO} and the SFE in the central region of M 83 seems to be almost coincident with that of Gao and Solomon (2004a) sample. This suggests that the correlation between R_{HCN/CO} and the SFE on a GMA (≈ 160 pc) scale found in the nuclear starburst region of M 83 is the origin of the global correlation on a few kpc scale shown by Gao and Solomon (2004a).

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