ASTE CO (3–2) Observations of the Southern Barred Spiral Galaxy NGC 986: a Large Gaseous Bar Filled with a Dense Molecular Medium

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Abstract

We present CO (3–2) emission observations toward the $3' \times 3'$ (or 20 kpc \times 20 kpc at a distance of 23 Mpc) region of the southern barred spiral galaxy NGC 986 using the Atacama Submillimeter Telescope Experiment (ASTE). This effort is a part of our on-going extragalactic CO (3–2) imaging project, ADIoS (ASTE Dense gas Imaging of Spiral galaxies). Our CO (3–2) image revealed the presence of a large (the major axis is 14 kpc in total length) gaseous bar filled with a dense molecular medium along the dark lanes observed in optical images. This is the largest “dense-gas rich bar” known to date. The dense gas bar, discovered in NGC 986, could be a huge reservoir of possible “fuel” for future starbursts in the central region, and we suggest that star formation in the central region of NGC 986 could still be in a growing phase. We found a good spatial coincidence between the overall distributions of dense molecular gas traced by CO (3–2) and massive star formation depicted by Hα. The global CO (3–2) luminosity, $L_{\text{CO}(3-2)}^\star$, of NGC 986 was determined to be $(5.4 \pm 1.1) \times 10^8$ K km s$^{-1}$ pc$^2$. The CO (3–2)/CO (1–0) integrated intensity ratio was found to be 0.60 ± 0.13 at a spatial resolution of 44′′ or 5 kpc, and the CO (3–2)/CO (2–1) ratio was 0.67 ± 0.14 at a beam size of ~25″ or ~2.8 kpc. These line ratios suggest moderate excitation conditions of CO lines ($n_{\text{H}_2} \sim 10^3$–$10^4$ cm$^{-3}$) in a few kiloparsec region of central NGC 986.

Key words: galaxies: individual (NGC 986) — galaxies: ISM — galaxies: starburst — galaxies: structure — submillimeter

1. Introduction

The dense molecular medium is one of the indispensable components to understand the star-formation law in galaxies. This is because stars are formed from dense molecular cores, not from the diffuse envelopes of giant molecular clouds (GMCs). In fact, extragalactic observations of millimeter-wave HCN (1–0) emission, which is a tracer of a high-density molecular medium ($n_{\text{H}_2} \sim 10^5$ cm$^{-3}$), due to its high permanent dipole moment ($\mu = 3.0$ debye), demonstrate that the correlation between HCN (1–0) and the far-infrared (FIR) luminosities is better than that between CO (1–0) and the FIR luminosities (Solomon et al. 1992; Gao & Solomon 2004a). However, the weakness of HCN emission [typically 1/10 in $T_0$ of CO in the central regions of galaxies, and 1/30–1/50 of CO in the disk regions of the Galaxy (Helfer & Blitz 1997) and galaxies (Helfer & Blitz 1993; Kohno et al. 1996, 1999, 2003; Gao & Solomon 2004b)] often prevents us from obtaining large-scale maps of the dense molecular medium through HCN observations.

In order to understand the global distribution of a dense molecular medium in galaxies, we have conducted an extragalactic CO (3–2) imaging survey of nearby spiral galaxies, ADIoS (ASTE Dense gas Imaging of Spiral galaxies). The current sample galaxies of the ADIoS project are listed in table 1. The submillimeter-wave CO (3–2) emission is another tracer of dense gas, because its Einstein A coefficient is proportional to $v^2$; therefore, the critical density of CO (3–2) emission is higher than that of CO (1–0) by a factor of ~3$^3$, i.e., $n_{\text{H}_2} \sim 10^5$ cm$^{-3}$.

The Atacama Submillimeter Telescope Experiment (ASTE: Ezawa et al. 2004), a new project to operate a 10 m telescope in

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the Atacama Desert of northern Chile, provides us with an ideal opportunity to generate large-scale maps of CO (3–2) emission, because of the high beam efficiency of the telescope, a low system noise temperature due to the good receiver system and atmospheric conditions at the site, and its efficient on-the-fly (OTF) mapping capability (Sawada et al. 2008).

Here, we present CO (3–2) images of the southern CO luminous spiral galaxy NGC 986 as the initial result of the ADIoS project by using OTF mapping. NGC 986 is a nearby (\(D = 23.2\) Mpc: Tully 1988) barred spiral galaxy accompanied by an outer pseudo-ring (i.e., \(R_{\text{ps}}\)) (Buta 1995). It is a member of the IRAS bright galaxy sample (Sanders et al. 2003); however, its FIR luminosity is rather moderate (\(L_{\text{FIR}} = 3.5 \times 10^{10} L_\odot\)).\(^1\) The nucleus is classified as H II (Veron-Cetty & Veron 1986), and extended massive star forming regions along the bar have been imaged in H\alpha (Hameed & Devereux 1999; Koopmann & Kenney 2006) and a mid-infrared continuum (Dale et al. 2000; see also Förster Schreiber et al. 2004). The central region of NGC 986 is very rich in interstellar medium (ISM), and there are many reports on the observations of various atomic lines in the near-infrared (NIR) to FIR regions (Kawara et al. 1987, 1989; Thorley et al. 2000; Malhotra et al. 2001) and molecular lines at millimeter wavelengths (Aalto et al. 1991, 1995; Elfhag et al. 1996). In fact, NGC 986 is one of the brightest galaxies in terms of CO (1–0) emission in the sample of Elfhag et al. (1996), thereby rendering this galaxy as an ideal target for our ADIoS project. It should be noted that all of the previous CO observations of NGC 986 were conducted just toward the central position, and no CO map of NGC 986 has yet been published. These properties of NGC 986 are summarized in table 3.

2. Observations and Data Reduction

CO (3–2) observations towards NGC 986 were conducted using the ASTE on 2006 September 14 and 15. The total time for the observation was 10 hours. The mapped region was \(3'\times3'\) (20 kpc \(\times\) 20 kpc), covering almost the entire region of the optical disk. The half-power beam width (HPBW) of the ASTE 10 m dish is \(22''\) at this frequency; this corresponds to 2.5 kpc at a distance of 23 Mpc.

The frontend was a cartridge-type cooled SIS mixer receiver for the DSB operation, SC345 (Kohno 2005; Muraoka 2007). The backend was a digital autocorrelator system, MAC (Sorai et al. 2000b), which is comprised of four banks of a 512 MHz wide spectrometer with 1024 spectral channels each. This arrangement provided a velocity coverage of 440 km s\(^{-1}\) with a velocity resolution of 0.43 km s\(^{-1}\). The observations were made remotely from an ASTE operation room of NRO using a network observation system, N-COSMOS3, developed by the National Astronomical Observatory of Japan (NAOJ) (Kamazaki et al. 2005).

OTF mapping was performed along two different directions (i.e., scans along the RA and Dec directions), and these two data sets were co-added by the Basket-weave method (Emerson & Gräve 1988) in order to remove any effects of scanning noise. At the end of each OTF scan, an off-source position (\(5'\) offset from the map center in the azimuth) was observed to subtract sky emission.

We observed the CO (3–2) emission of \(\alpha\) Ceti (Mira) every 2 hours in order to monitor the stabilities of the pointing accuracy and the main beam efficiency (\(\eta_{mb}\)) of the ASTE 10 m dish. The pointing accuracy was found to be better than \(\sim 2''\) r.m.s., and \(\eta_{mb}\) was estimated to be 0.6 during the observing runs. The absolute error of the CO (3–2) amplitude scale was \(\sim \pm 20\%\), mainly due to a variation in the beam efficiency.

The data reduction was made using the software package NOSTAR, which comprises tools for OTF data analysis, developed by NAOJ (Sawada et al. 2008). The raw data were regulated to 8" per pixel, giving an effective spatial resolution of approximately 25" (or 2.8 kpc). Linear baselines were removed from the spectra. We binned the adjacent channels to a velocity resolution of 10 km s\(^{-1}\) at a frequency of CO (3–2). The resultant r.m.s. noise level (1 \(\sigma\)) was around 25 mK on the \(T_{mb}\) scale or 1.5 Jy beam\(^{-1}\) at a beam size of 25'' (HPBW). It is noteworthy that at this frequency and beam size, a brightness temperature of 1 K on the \(T_{mb}\) scale corresponds to a flux density of 60.7 Jy beam\(^{-1}\).

After producing a 3D data cube, we analyzed it using AIPS. The 0th and 1st moment maps were computed using a clip level of 50 mK (or 2 \(\sigma\)) by the AIPS task MOMNT. A three-channel Hanning smoothing along the velocity axis was applied in order to mitigate the contribution from noise.

3. Results

3.1. Channel Maps, Spectrum, and Moment Maps

The derived velocity channel maps of CO (3–2) emission in NGC 986 are displayed in figure 1. We find a strong concentration of CO emission toward the center with a large velocity width [from 1865 to 2015 km s\(^{-1}\); see also the CO (3–2) spectrum at the central position in figure 2]; however, the extended

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Table 1. Sample galaxies of the ADIoS project.

| Object       | Map size | Mode* | Reference          | Complementary CO (1–0) data |
|--------------|---------|-------|--------------------|-----------------------------|
| M 83         | 5'\times5' | PS    | Muraoka (2007)     | NRO 45 m (Kuno et al. 2007) |
| a GMA in M 31 | 1.5'\times1.5' | PS    | Tosaki et al. (2007a) | NRO 45 m (Tosaki et al. 2007a) |
| NGC 986      | 3'\times3'  | OTF   | this work          | NRO 45 m (Sorai et al. 2000a) |
| NGC 253      | 9'\times3'  | OTF   | K. Nakanishi et al. unpublished | NRO 45 m (Tosaki et al. 2007b) |
| NGC 604 (in M 33) | 5'\times5'  | OTF   | Tosaki et al. (2007b) | NRO 45 m (Tosaki et al. 2007b) |

*PS = position switching, OTF = on-the-fly mapping.
Fig. 1. Velocity channel maps of the CO (3–2) emission in NGC 986 obtained by ASTE. Contour levels are 2, 4, 6, 8, 10, 15, 20, and 25 $\sigma$, where $1\sigma = 25$ mK on the $T_{\text{mb}}$ scale or 1.5 Jy beam$^{-1}$. Each map is labeled by the LSR velocity in km s$^{-1}$. The central cross in each panel indicates the position of the nucleus (defined by the peak position of the NIR continuum from 2MASS/NED).

Fig. 2. ASTE CO (3–2) spectrum at the central position of NGC 986. The effective spatial resolution (see section 2) of the spectrum is 25" (HPBW). The peak temperature of approximately 0.6 K corresponds to 36 Jy beam$^{-1}$.

emission along the SW to NE direction in some velocity channels (from 1925 to 1985 km s$^{-1}$) is also evident.

The 0th and 1st moment maps, i.e., a velocity integrated intensity map and an intensity-weighted mean velocity map, respectively, are shown in figure 3. The peak position of CO (3–2) emission, fitted by the AIPS task IMFIT, coincides well with the NIR peak within an accuracy of less than 1".

In addition to the strong CO condensation at the center, we can clearly see extensions of the CO emission along the bar and outer spiral arms, as observed in the R-band and H$\alpha$ images (Hameed & Devereux 1999). The major axis of this gaseous bar seen in CO (3–2) emission is $\sim 2'$ or 14 kpc. The nature of the gaseous bar is discussed in section 4.

3.2. Spatial Coincidence between CO (3–2) and H$\alpha$ Emissions

In figure 3d, we find a good spatial coincidence between the overall distributions of dense molecular gas traced by CO (3–2) and the massive star formation depicted by H$\alpha$ at a spatial scale of $\sim 3$ kpc. This is expected from recent CO (3–2) observations that demonstrate a tight correlation
between CO (3–2) and Hα luminosities (Komugi et al. 2007), thereby indicating an intimate association of the dense molecular medium with massive star formation (see also Yao et al. 2003). It is intriguing to study whether CO (3–2) emission also shows a better spatial coincidence with the massive star-forming regions as compared to the low-density gas traced by the CO (1–0) emission. In fact, previous surveys of CO (3–2) and CO (1–0) lines toward the centers of star-forming galaxies suggest that CO (3–2) luminosities show a tighter correlation with the star-formation rates (traced by Hα or FIR) than that of the CO (1–0) luminosities (Komugi et al. 2007; Yao et al. 2003) Future high-resolution low- J CO observations might be able to address this issue.

### 3.3. Global CO (3–2) Luminosity

The total CO (3–2) flux of NGC 986 was measured using the AIPS task TVSTAT. The mean CO (3–2) intensity was 4.5 K km s⁻¹, averaged over 147 pixels, or 1.2 × 10³ pc².
This gives a global CO (3–2) luminosity, \( L_{\text{CO(3–2)}} \), of \((5.4 \pm 1.1) \times 10^8\) in units of K km s\(^{-1}\) pc\(^2\). Note that the quoted error represents the systematic uncertainty, mainly due to the accuracy of the main beam efficiency (±20%). The derived CO (3–2) luminosity of NGC 986 is comparable with that of the inner \( S' \times S' \) region of M 83 (Muraoka 2007).

### 3.4. CO (3–2)/(CO (1–0)) and CO (3–2)/(CO (2–1)) Intensity Ratios

We compared the CO (3–2) intensity that we obtained at the central position with the existing CO (1–0) (Aalto et al. 1991; Elfhag et al. 1996) and CO (2–1) (Aalto et al. 1995) measurements. All of the previous observations were made using the SERT 15 m telescope. In order to compare our CO (3–2) data with the low-resolution (43\(^\circ\) or 44\(^\circ\) resolution) CO (1–0) intensities, we convolved our CO (3–2) cube to the same spatial resolution (44\(^\circ\)). The SERT CO (2–1) observations had a beam size similar to that of the ASTE CO (3–2) observations, and no correction was made in the derivation of the CO (3–2)/CO (2–1) line ratio. The integrated intensities of various CO transitions were then summarized (in table 2).

\[
\begin{array}{cccccc}
\text{Transition} & \text{Integrated intensity} & \text{Telescope} & \text{Beam efficiency} & \text{Beam size} & \text{Reference} \\
\hline
\text{CO (1–0)} & 33.4 \pm 0.6 & \text{SERT 15 m} & 0.7 & 43 & \text{Aalto et al. 1991} \\
\text{CO (2–1)} & 82.4 \pm 1.2 & \text{SERT 15 m} & 0.5 & 24 & \text{Aalto et al. 1995} \\
\text{CO (3–2)} & 21.3 \pm 0.33 \pm 4.3^* & \text{ASTE 10 m} & 0.6 & 25 & \text{this work} \\
\end{array}
\]

\* The first error corresponds to the S/N of the spectrum (i.e., random error only), and the second error is obtained from the systematic error, mainly due to the accuracy of the main beam efficiency (20%).

Measurements are a few hundred parsec to a few kiloparsec scales, and therefore a mixture of multiple ISM components must be observed.

The observed line ratios in NGC 986 suggest a moderate excitation condition of the CO lines within a few kiloparsec central region of this galaxy. For instance, \( R_{3–2/1–0} \) of 0.7 suggests that the mean gas density, \( n_{\text{H}_2} \), averaged over a \( \sim 2.8\) kpc region in diameter is within a range of \( 10^3 \) to \( 10^4\) cm\(^{-3}\), based on an LVG model by assuming a kinetic temperature of 30 K (see figure 8 of Hafok & Stutzki 2003 for instance). Additional mapping observations of low-J CO lines will be essential to determine the spatial distribution of CO line ratios, allowing us to impose constraints on the physical properties of ISM for various positions in NGC 986.

### 3.5. Molecular Gas Mass

From our global CO (3–2) luminosity of NGC 986, the total molecular gas mass was estimated to be

\[
M(H_2) = 2.6 \times 10^9 \left( \frac{a_{\text{CO}}}{2.9} \frac{M_\odot}{(\text{K km s}^{-1}\text{pc}^2)^{-1}} \right) \left( \frac{R_{3–2/1–0}}{0.6} \right)^{-1} M_\odot.
\]

Here, we adopted a Galactic CO (1–0)-to-H\(_2\) conversion factor, \( a_{\text{CO}} = 2.9 M_\odot (\text{K km s}^{-1}\text{pc}^2)^{-1} \) [equivalent to \( X_{\text{CO}} = 1.8 \times 10^{20} \text{cm}^{-2} (\text{K km s}^{-1})^{-1} \): Dame et al. 2001] and a CO (3–2)/(CO (1–0)) ratio \( R_{3–2/1–0} \) of 0.6 (see subsection 3.4). This molecular gas mass is comparable to those in nearby gas-rich spiral galaxies, such as M 51 (6 \( \times 10^9 M_\odot \); Kuno et al. 1995) and M 83 (3–4 \( \times 10^9 M_\odot \); Crosthwaite et al. 2002; Lundgren et al. 2004).

### 3.6. Star-Formation Efficiency

The star-formation efficiency (SFE), the star formation rate per unit gas mass, is then \( L_{\text{FIR}} / M(H_2) = 14 L_\odot / M_\odot \). Note that both \( L_{\text{FIR}} \) and \( M(H_2) \) were measured over almost the entire region of this galaxy (i.e., determined for the same area). This SFE in NGC 986 is indeed close to the SFEs of nearby isolated or field spiral galaxies, \( L_{\text{FIR}} / M(H_2) \sim 3–5 L_\odot / M_\odot \) (Young et al. 1996). Note that Young et al. (1996)
Table 3. Properties of NGC 986.

| Parameter                             | Value                      | Reference |
|---------------------------------------|----------------------------|-----------|
| Distance                              | 23.2 Mpc                   | (1)       |
| Scale                                 | 112 pc/"                   |           |
| Morphology                            | (R)SB(rs)b                 | (2)       |
| Position of nucleus RA (J2000.0)      | 02h33m34.35                | (3)       |
| Dec (J2000.0)                         | −39°02′42.2″               |           |
| Systemic velocity (LSR)              | 1969 km s⁻¹               | (4)       |
|                                       | 1945 km s⁻¹               | (5)       |
|                                       | 1942 ± 10 km s⁻¹           | this work |
| Inclination (0° is face-on)           | 42°                       | (1)       |
|                                       | 41°                       | (6)       |
|                                       | 55°                       | (7)       |
|                                       | 37°                       | this work |
| Position angle (from north to east)   | 150°                      | (6)       |
|                                       | 127°                      | (7)       |
|                                       | 127°                      | this work |
| Global FIR luminosity $L_{\text{FIR}}$| $3.5 \times 10^{10} L_\odot$| (8)       |
| Global CO (3–2) luminosity $L_{\text{CO (3–2)}}$| $(5.4 \pm 1.1) \times 10^8$ K km s⁻¹ pc² | this work |
| Molecular gas mass $M_{\text{H}_2}$  | $2.6 \times 10^8 M_\odot$  | this work |
| Star formation efficiency $L_{\text{FIR}}/M_{\text{H}_2}$ | $14 L_\odot/M_\odot$ | this work |
| Star formation efficiency $L_{\text{FIR}}/L_{\text{CO (3–2)}}$ | $67 L_\odot/(K$ km s⁻¹ pc²) | this work |

To obtain the heliocentric velocity, add 15 km s⁻¹ to the velocity in LSR.

Assuming $X_{\text{CO}} = 2.8 \times 10^{20}$ cm⁻² (K km s⁻¹)⁻¹; if we recalibrate the SFEs using the same $X_{\text{CO}}$ value as for NGC 986 (Dame et al. 2001), the SFEs for nearby isolated or field spirals will be $\sim 5–8 L_\odot/M_\odot$, which are more closer to that of NGC 986. On the other hand, the observed SFE in NGC 986 is much lower than those in local IR luminous galaxies, $L_{\text{FIR}}/M_{\text{H}_2} \sim 120 L_\odot/M_\odot$ (a mean value computed from table 2 of Yoon et al. 2003). Here, Yoon et al. (2003) determined $X_{\text{CO}}$ of their sample to be $2.7 \times 10^{19}$ cm⁻² (K km s⁻¹)⁻¹, about 1/10 of a typical Galactic CO-to-H₂ conversion factor.

Another direct quantity related to SFE is the FIR to CO (3–2) luminosity ratio, $L_{\text{FIR}}/L_{\text{CO (3–2)}}$, a measure of star formation rate per unit dense-gas mass. We find the $L_{\text{FIR}}/L_{\text{CO (3–2)}}$ ratio to be $67 L_\odot/(K$ km s⁻¹ pc²) in NGC 986. This is comparable to the $L_{\text{FIR}}/L_{\text{CO (3–2)}}$ values found in local IR luminous galaxies, a few $10 L_\odot/(K$ km s⁻¹ pc²), which was calculated from Yoon et al. (2003), yet still much smaller than Ultra/Hyper luminous IR galaxies in the early universe, such as the submillimeter galaxy MIPS J142824.0+352619 at $z = 1.3$, showing an $L_{\text{FIR}}/L_{\text{CO (3–2)}}$ of $264 \pm 84 L_\odot/(K$ km s⁻¹ pc²) (Iono et al. 2006).

3.7. Kinematics of Dense Molecular Gas

We found a clear velocity gradient in the mean-velocity map (figure 3b). We therefore determined the kinematical parameters of the gas disk, i.e., the dynamical center, the systemic velocity, the position angle of the major axis, and the inclination angle of the disk by a least-squares fitting of the intensity-weighted isovelocity field to a circular rotation model. The AIPS task GAL was used for this analysis. The fitting was made within a radius of 1′, where the observed velocity field seems to be dominated by a circular motion. In general, strong non-circular motions are expected in the central regions of barred galaxies, but it is not clear in our map; it could be probably due to the insufficient spatial resolution of our observations.

The dynamical center coincides well with the nucleus position determined by the NIR (2MASS) peak within an error of a few arcseconds. The systemic velocity (LSR) was determined to be $1942 \pm 10$ km s⁻¹ (or corresponding to a heliocentric velocity of $1957 \pm 10$ km s⁻¹). This agrees well with the CO (1–0) result (Elfhag et al. 1996) and is close to the H I velocity measurement (Roth et al. 1994). See table 3 for
a comparison. The position angle of the major axis and the inclination angle of the disk were estimated to be 127° (from north to east) and 37° (0° is face-on), respectively. These kinematically determined angles are consistent with the previously reported isophotal values based on optical and NIR broad band images of NGC 986 (Tully 1988; de Vaucouleurs et al. 1991; Jarrett et al. 2003). A comparison of these angles is shown in table 3.

A position-to-velocity map (PV map) was generated along the determined major axis (PA = 53°), as shown in figure 4. The velocity gradient along the major axis was found to be \( \sim 10 \, \text{km s}^{-1} \, \text{arcsec}^{-1} \) from the figure; however, we require much higher angular resolution measurements of the PV map, using SMA for instance, in order to determine the inner rotation curve of NGC 986.

4. Discussion: A Large (~14 kpc) Gaseous Bar Filled with Dense Molecular Medium

Our CO (3–2) image revealed the presence of a large (~14 kpc) gaseous bar filled with a dense molecular medium along the dark lanes observed in the optical images. This is the largest “dense-gas rich bar” known to date; previous large-scale CO (3–2) imaging observations of nearby galaxies revealed that a centrally concentrated CO (3–2) morphology of around a few kiloparsec scale is very common (Hurt et al. 1993; Mauersberger et al. 1996; Israel & Baas 2001; Dumke et al. 2001; Israel & Baas 2003). Some gas-rich barred spiral galaxies, such as NGC 6946 (Israel & Baas 2001; Walsh et al. 2002), and M 83 (Israel & Baas 2001; Bayet et al. 2006; Muraoka et al. 2007), exhibit a wide spread CO (3–2) emission over the disk region; however, no such instances of large (~10 kpc scale) dense molecular gas bar have been reported thus far. Therefore, it is indeed a surprise to discover a 14 kpc long gaseous bar observed in CO (3–2) emission among nearby spiral galaxies. Note that this is even true in the case of bars observed in low-J CO lines. Some galaxies, such as NGC 1530 (Downes et al. 1996), UGC 2855 (Hüttemeister et al. 1999), and NGC 7479 (Sempere et al. 1995) do exhibit a continuous bar, were observed in CO (1–0) and/or CO (2–1) emission, with a length of ~10 kpc; however, this is a rare phenomenon.

The dense molecular medium in the bar region could be transported to the central region of NGC 986 within a short time scale (~ a dynamical time scale) due to strong shock along the bar (e.g., see Wada & Habe 1992 and references therein). This could be a major reason why we hardly observe such a gas-rich bar in galaxies (e.g., Hüttemeister et al. 1999). Therefore, the discovered dense gas bar in NGC 986 must be a huge reservoir of possible “fuel” for future starbursts in the central region, and we suggest that the star-formation process in the central region of NGC 986 could still be in a growing phase.

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References

Aalto, S., Black, J. H., Johansson, L. E. B., & Booth, R. S. 1991, A&A, 249, 323
Aalto, S., Booth, R. S., Black, J. H., & Johansson, L. E. B. 1995, A&A, 300, 369
Bayet, E., Gerin, M., Phillips, T. G., & Contursi, A. 2006, A&A, 460, 467
Buta, R. 1995, ApJS, 96, 39
Crosthwaite, L. P., Turner, J. L., Buchholz, L., Ho, P. T. P., & Martin, R. N. 2002, AJ, 123, 1892
Dale, D. A., et al. 2000, AJ, 120, 583
Dame, T. M., Hartmann, D., & Thaddeus, P. 2001, ApJ, 547, 792
de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H. G., Jr., Buta, R. J., Paturel, G., & Fouqué, P. 1991, Third Reference Catalogue of Bright Galaxies (New York: Springer-Verlag) (RC3)
Derveaux, N., Taniguchi, Y., Sanders, D. B., Nakai, N., & Young, J. S. 1994, AJ, 107, 2006
Downes, D., Reynaud, D., Solomon, P. M., & Radford, S. J. E. 1996, ApJ, 461, 186
Dumke, M., Nieten, Ch., Thuma, G., Wielebinski, R., & Walsh, W. 2001, A&A, 373, 853

Fig. 4. ASTE CO (3–2) position-to-velocity (PV) diagram along the major axis (PA = 127°; table 3) of NGC 986. Contour levels are 2, 4, 6, 8, 10, 15, 20, and 25 \( \sigma \), where \( \sigma = 25 \, \text{mK} \) on the \( T_{\text{mb}} \) scale or 1.5 Jy beam\(^{-1}\).
Elfhag, T., Booth, R. S., Hoeglund, B., Johansson, L. E. B., & Sandqvist, A. 1996, A&AS, 115, 439
Emerson, D. T., & Gräve, R. 1988, A&A, 190, 353
Ezawa, H., Kawabe, R., Kohno, K., & Yamamoto, S. 2004, Proc. SPIE, 5489, 763
Förster Schreiber, N. M., Roussel, H., Sauvage, M., & Charmandaris, V. 2004, A&A, 419, 501
Gao, Y., & Solomon, P. M. 2004a, ApJ, 606, 271
Gao, Y., & Solomon, P. M. 2004b, ApJS, 152, 63
Hafok, H., & Stutzki, J. 2003, A&A, 398, 959
Hameed, S., & Devereux, N. 1999, AJ, 118, 730
Helfer, T. T., & Blitz, L. 1993, ApJ, 419, 86
Helfer, T. T., & Blitz, L. 1997, ApJ, 478, 233
Hurt, R. L., Turner, J. L., Ho, P. T. P., & Martin, R. N. 1993, ApJ, 404, 602
Hüttemeister, S., Aalto, S., & Wall, W. F. 1999, A&A, 346, 45
Iono, D., et al. 2006, PASJ, 58, 957
Israel, F. P., & Baas, F. 2001, A&A, 371, 433
Israel, F. P., & Baas, F. 2003, A&A, 404, 495
Jarrett, T. H., Chester, T., Cutri, R., Schneider, S. E., & Huchra, J. P. 2000, AJ, 125, 525
Kamazaki, T., et al. 2005, ASP Conf. Ser. 347, 533
Kawara, K., Nishida, M., & Gregory, B. 1987, ApJ, 321, L35
Kawara, K., Nishida, M., & Phillips, M. M. 1989, ApJ, 337, 230
Kohno, K. 2005, in ASP Conf. Ser. 344, The Cool Universe: Observing Cosmic Dawn, ed. C. Lidman & D. Alloin (San Francisco: ASP), 242
Kohno, K., Ishizuki, S., Matsushita, S., Vila-Vilaró, B., & Kawabe, R. 2003, PASJ, 55, L1
Kohno, K., Kawabe, R., Tosaki, T., & Okumura, S. K. 1996, ApJ, 461, L29
Kohno, K., Kawabe, R., & Vila-Vilaró, B. 1999, ApJ, 511, 157
Komugi, S., et al. 2007, PASJ, 59, 55
Koopmann, R. A., & Kenney, J. D. P. 2006, ApJS, 162, 97
Kuno, N., et al. 2007, PASJ, 59, 117
Kuno, N., Nakai, N., Handa, T., & Sofue, Y. 1995, PASJ, 47, 745
Lundgren, A. A., Wiklind, T., Olofsson, H., & Rydbeck, G. 2004, A&A, 413, 505
Malhotra, S., et al. 2001, ApJ, 561, 766
Mauersberger, R., Henkel, C., Walsh, W., & Schulz, A. 1999, A&A, 341, 256
Mauersberger, R., Henkel, C., Whiteoak, J. B., Chin, Y.-N., & Tiefe, R. 1996, A&A, 309, 705
Meier, D. S., Turner, J. L., Crothwaite L. P., & Beck, S. C. 2001, AJ, 121, 740
Muraoka, K., et al. 2007, PASJ, 59, 43
Oka, T., et al. 2007, PASJ, 59, 15
Roth, J., Mould, J., & Staveley-Smith, L. 1994, AJ, 108, 851
Sanders, D. B., Mazzarella, J. M., Kim, D.-C., Surace, J. A., & Soifer, B. T. 2003, AJ, 126, 1607
Sanders, D. B., Scoville, N. Z., Tilanus, R. P. J., Wang, Z., & Zhou, S. 1993, in AIP Conf. Proc. 278, Back to the Galaxy, ed. S. S. Holt, F. W. Olin, & F. Verter (Melville: AIP), 311
Sawada, T., et al. 2008, PASJ, 60, 445
Sempere, M. J., Combes, F., & Casoli, F. 1995, A&A, 299, 371
Solomon, P. M., Downes, D., & Radford, S. J. E. 1992, ApJ, 387, L55
Sorai, K., Nakai, N., Kuno, N., Nishiyama, K., & Hasegawa, T. 2000a, PASJ, 52, 785
Sorai, K., Sunada, K., Okumura, S. K., Tetsuro, I., Tanaka, A., Natori, K., & Onuki, H. 2000b, Proc. SPIE, 4015, 86
Thornley, M. D., Förster Schreiber, N. M., Lutz, D., Genzel, R., Spoon, H. W. W., Kunze, D., & Sternberg, A. 2000, ApJ, 539, 641
Tosaki, T., Miura, R., Sawada, T., Kuno, N., Nakanishi, K., Kohno, K., Okumura, S. K., & Kawabe, R. 2007b, ApJ, 664, L27
Tosaki, T., Shiota, Y., Kuno, N., Hasegawa, T., Nakanishi, K., Matsushita, S., & Kohno, K. 2007a, PASJ, 59, 33
Tully, R. B. 1988, Nearby Galaxies Catalogue (Cambridge: Cambridge Univ. Press)
Véron-Cetty, M.-P., & Véron, P. 1986, A&AS, 66, 335
Vila-Vilaró, B., Cepa, J., & Butner, H. M. 2003, ApJ, 594, 232
Wada, K., & Habe, A. 1992, MNRAS, 258, 82
Walsh, W., Beck, R., Thuma, G., Weiss, A., Wielebinski, R., & Dunke, M. 2002, A&A, 388, 7
Yao, L., Seaquist, E. R., Kuno, N., & Dunne, L. 2003, ApJ, 588, 771
Young, J. S., Allen, L., Kenney, J. D. P., Lesser, A., & Rownd, B. 1996, AJ, 112, 1903