Virgo High-Resolution CO Survey: V. Circumnuclear Elliptical Ring in NGC 4569

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Abstract

We present high-resolution (1′′8 – 4′′5) CO data of the Virgo spiral galaxy NGC 4569, obtained using the Nobeyama Millimeter Array. We found that the molecular gas is highly concentrated in the circumnuclear region with two off-center peaks. A CO image with the highest angular resolution of 2′′0 × 1′′8 shows that six blobs likely form a circumnuclear elliptical ring (CER) with a semi-major axis radius of 720 pc. The CER shows a strongly twisted velocity field, and the position–velocity (PV) diagram shows significant forbidden velocity components. These kinetic features are understood as being non-circular motion due to a bar-potential. We found that the CER coincides with the Hβ bright central core and that the mass ratio of the molecular gas to the dynamical mass is about 18%. These results support a gaseous inflow scenario induced by a weak bar potential and self-gravity of the gas.

Key words: galaxies: clusters: individual (Virgo) — galaxies: individual (NGC 4569, M 90) — galaxies: ISM — galaxies: kinematics and dynamics — galaxies: spiral

1. Introduction

NGC 4569 is a member of the Virgo cluster galaxies and its nucleus is classified as a starburst-dominated LINER (Alonso-Herrero et al. 2000). The mechanism for causing nuclear activity is still unveiled. A CO line observation is useful to explore the physical conditions of the central regions of spiral galaxies to understand this issue, because the molecular gas is a dominant component among neutral gases in the central region.

Sakamoto et al. (1999) observed this galaxy using the Nobeyama Millimeter Array (NMA) at the Nobeyama Radio Observatory (NRO) in the 12CO(J = 1–0) line, and obtained a resolution of 3′09 × 3′06. They showed the gas concentration in the central region, two significant peaks on the central concentration, and strong non-circular motions. Helfer et al. (2003) obtained 12CO(J = 1–0) line data with a resolution of 6′6 × 5′5 in the BIMA SONG project. They found extended CO emission up to about 1′ radius.

In order to investigate the more detail kinematics in the central region of spiral galaxies, we achieved the Virgo high-resolution CO-line survey (ViCS) during a long-term project at the NMA from 1999 December to 2000 March to obtain the highest resolution CO data (Sofue et al., 2003, Paper I hereafter). We presented CO data of NGC 4569 with low-resolution (4′5 × 3′1) in Paper I. In this paper as Part V of the series of the ViCS, we present the highest resolution (2′′0 × 1′′8) CO data, and discuss the distribution of the interstellar matter (ISM) in the central region and the relationship to the nuclear activity.

An optical B-band image of this galaxy is shown in figure 1, which was taken from STScI Digitized Sky Survey (DSS). The properties of this galaxy are summarized in table 1. NGC 4569 is assumed to be at a distance of 16.1 Mpc, which is the distance of the Virgo cluster member NGC 4321 (Ferrarese et al. 1996). The angular size of 1′′ corresponds to 78 pc. A position angle (P.A.) of 18° and an inclination of 63° are adopted (Nakanishi 2004).

— Figure 1 —

— Table 1 —

2. Observation and Reduction

We carried out interferometer observations of the central region of NGC 4569 in the 12CO (J = 1–0) line using the NMA in the AB, C, and D configurations. D, AB, and C-configuration observations were made in 1999 December, 2000 February, and 2000 March, respectively, as a part of the ViCS project.

The observation time was typically 7 – 8 hours per each configuration. The pointing center was at RA(J2000) = 12h36m49.82s, Dec(J2000) = +13°09′45.08″, adopted from Sakamoto et al. (1999). For flux and phase calibrations, we observed the nearby radio point source 3C 273 every 20 minutes with an integration time of 3 minutes. We calibrated the flux against NRAO 530, 1749+096, and 0507+179. The fluxes of the gain calibrator, 3C 273, were 11.2 Jy in the D-configuration observation, 10.4 Jy in the AB-configuration observation, and 11.2 Jy in the C-configuration observation. The obtained fluxes contained errors of ~20%. We used a spectro-correlator system, Ultra Wide Band Correlator (UWBC) (Okumura et al. 2000), in a narrow-band mode, which had 256 channels and...
the total bandwidth of 512 MHz. One channel corresponded to 5.2 km s\(^{-1}\) at the observing frequency. Table 2 gives the observational parameters.

— Table 2 —

The raw data were calibrated using the reduction software UVPROC-II, developed at NRO. A baseline correction, a system temperature \(T_{\text{sys}}\) correction, a bandpass calibration, and a flux calibration were applied. The calibrated UV data were Fourier-transformed using the National Radio Astronomy Observatory (NRAO) Astronomical Image Processing System (AIPS) to derive CO images. We adopted the CLEAN method to derive CO images. We adopted the CLEAN method and applied two different weighting functions for the UV data, to produce two maps with different resolutions and sensitivities (see table 3).

We first obtained a CO image using a natural weighting function. The data were averaged in 2 bins (10.4 km s\(^{-1}\)) of the original channels, and the channel increment was 2 (10.4 km s\(^{-1}\)), yielding a 128-channel data cube. A pixel size of 0\('5\) was adopted for the mapping. The synthesized beam size (full width half maximum; FWHM) was 4\('5\) \(\times\) 3\('1\), and the typical r.m.s. noise on a channel map was 23 mJy per beam.

Second, we obtained a high-resolution map using a uniform weighting function. The data were averaged in 4 bins, giving a velocity resolution of 20.8 km s\(^{-1}\). The channel increment was fixed at 2 (10.4 km s\(^{-1}\)). The synthesized beam size (FWHM) was 2\('0\) \(\times\) 1\('8\), which was the highest resolution among ever obtained data. The typical r.m.s. noise was 34 mJy per beam. The parameters of the maps are given in table 3.

— Table 3 —

3. Results

In this section, we present the obtained spectra, channel maps, CO intensity maps, a velocity field, Position–Velocity (PV) diagrams, and comparisons with the optical broadband, H\(\alpha\), and H \(\text{I}\) images. The highest resolution CO map first shows that there may exist an elliptical ring in the circumnuclear region (subsection 3.3), which has strong non-circular motions due to a bar-potential (subsections 3.4 and 3.5).

3.1. Spectra

Figure 2 shows CO line spectra at the center of NGC 4569. The top and bottom panels present spectra of the low- and high-resolution maps, respectively. In order to compare them with a single dish flux from the NRO 45 m telescope (FWHM = 16\(')\), the data were corrected for primary beam attenuation, convoluted with a Gaussian profile (FWHM = 16\(')\), and sampled at the pointing center. The integrated intensities of the low- and high-resolution maps were 149 K km s\(^{-1}\) and 96 K km s\(^{-1}\), respectively. The Nobeyama 45-m telescope observation of NGC 4569 (Nishiyama, Nakai, 2001) showed an integrated intensity of 134 K km s\(^{-1}\).

The fractions of the single-dish flux recovered by the aperture synthesis observations were 111% and 71% in the cases of the low- and high-resolution maps, respectively. The spectrum at the bottom of figure 2 is weaker than that at the top, because the missing flux is larger in the high-resolution map than in the low-resolution map.

— Figure 2 —

3.2. Channel Maps

Figure 3 shows channel maps of the central 35\(')\) region obtained with a uniform weighting. The increment of contiguous channels is 10.4 km s\(^{-1}\), although the maps were the averages over a velocity width of 20.8 km s\(^{-1}\). The CO emissions move from south-west to north-east as the radial velocity changes from blue-shift to red-shift, which indicates rotation of the galaxy.

— Figure 3 —

3.3. CO Intensity Maps

We derived integrated CO intensity maps (zeroth moment maps) from the obtained data cubes using the task MOMNT in AIPS. We show two maps, i.e. low- and high-resolution maps, derived using the two different weighting functions in CLEAN.

3.3.1. Natural weighting map

The low-resolution map, which was obtained using a natural weighting function, is shown in the top panel of figure 4. The molecular gas is highly concentrated into the central compact region. This molecular disk is elongated in the north-east (south-west) direction. The semi-major axis radius is about 12\(')\) by tracing the contour of 120 K km s\(^{-1}\) in the top panel of figure 4, which corresponds to 1.6 kpc. The molecular disk has two off-center peaks, and the south-western one is brighter than the other. In addition, two diffuse ridges run from the central concentration toward the north and south directions. These are the so-called offset ridges, which are often seen in barred galaxies.

— Figure 4 —

We present a radial distribution of the molecular gas in figure 5, which was obtained by using the task IRING. To make this figure, the primary beam attenuation was corrected. The surface density was calculated by adopting a CO-to-H\(_2\) conversion factor of \(C = 2.1 \times 10^{20} \text{cm}^{-2} \text{K}^{-1} \text{km s}^{-1}\) (Arimoto et al. 1996) and multiplying by cos63\(^\circ\) to take into account the inclination. The radial distribution of the molecular surface mass density, \(\Sigma \left[M_\odot \text{pc}^{-2}\right]\), can be well reproduced with an exponential function,

\[
\Sigma = \Sigma_0 \exp\left(-R/R_e\right),
\]

(1)

where \(\Sigma_0\) is the central surface density (670 \(M_\odot \text{pc}^{-2}\)), \(R\) is the radius, and \(R_e\) is the e-folding radius of 0.58 kpc. Integrating this function, the total gas mass, i.e. within the radius of 12\(')\) = 0.94 kpc, is 6.8 \(10^8 \ M_\odot\). The data do not suffer from the missing flux (see subsection 3.1).

The CO distribution presented in the top panel of figure 4 is consistent with Sakamoto et al. (1999).

— Figure 5 —
3.3.2. Uniform weighting map

The highest resolution map, which was obtained with a uniform weighing function, is shown in the bottom panel of figure 4. The map shows that the molecular gas is distributed like an elliptical ring (figure 6). This feature is in fact elliptical in a face-on view after correcting for the inclination using the same inclination angle and position angle of the major axis as the main disk. A face-on view of this ring is shown in the right panel of figure 6. We call this feature the circumnuclear elliptical ring (CER). CER consists of six major molecular blobs with peak intensities brighter than 300 K km s\(^{-1}\). The positions of these blobs are indicated by white crosses. In order to calculate the CER and these blobs may be related to the central activity, we summed up the larger intensities than thresholds: 300 K km s\(^{-1}\). The CER and these blobs may result in collisional dissipation between blobs and central starburst activity. The formations of these images was determined by comparing them with the DSS R-band image. The H\(^{\alpha}\) emission consists mainly of the central bright core and a ring with a radius of \(\sim 1\)'. The center ring is shifted toward the north-west direction. The central bright core is located inside the molecular CER.

The peak-positions, peak-integrated intensity, and the masses are given in table 6. The position angles of the major and minor axes were calculated by the least squares method. The central position was fixed at the mean position of the six blobs, and then, the radii and the position angles of the major and minor axes were calculated by the least squares method. The central position of this ellipse is indicated with an asterisk symbol in figure 6. This feature is in fact elliptical in a face-on view after correcting for the inclination using the same inclination angle and position angle of the major axis as the main disk. A face-on view of this ring is shown in the right panel of figure 6. We call this feature the circumnuclear elliptical ring (CER). CER consists of six major molecular blobs with peak intensities brighter than 300 K km s\(^{-1}\). The peak positions of these blobs are indicated by white crosses. In order to calculate the masses of the blobs, we summed up the larger intensities than thresholds: 300 K km s\(^{-1}\) for blobs 'D' and 'F', and 360 K km s\(^{-1}\) for the others. The masses range from \(5.44 \times 10^8 M_\odot\) to \(1.39 \times 10^8 M_\odot\), which were corrected for the missing flux of 29% and the primary beam attenuation. The peak-positions, peak-integrated intensity, and the masses are given in table 6.

In order to measure the radii of the major and minor axes, the axial ratio, the central position, and the position angle of the CER, we fitted an ellipse into the CER. The central position was fixed at the mean position of the six blobs, and then, the radii and the position angles of the major and minor axes were calculated by the least squares method. The central position of this ellipse is indicated with an asterisk symbol in figure 6. This feature is in fact elliptical in a face-on view after correcting for the inclination using the same inclination angle and position angle of the major axis as the main disk. A face-on view of this ring is shown in the right panel of figure 6. We call this feature the circumnuclear elliptical ring (CER). CER consists of six major molecular blobs with peak intensities brighter than 300 K km s\(^{-1}\). The peak positions of these blobs are indicated by white crosses. In order to calculate the masses of the blobs, we summed up the larger intensities than thresholds: 300 K km s\(^{-1}\) for blobs 'D' and 'F', and 360 K km s\(^{-1}\) for the others. The masses range from \(5.44 \times 10^8 M_\odot\) to \(1.39 \times 10^8 M_\odot\), which were corrected for the missing flux of 29% and the primary beam attenuation. The peak-positions, peak-integrated intensity, and the masses are given in table 6.

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The right panel of figure 10 shows the central region of this image. The CER is located at the bright Hα core. The central Hα bright core implies that a central starburst is occurring. We discuss the relationship between the bright Hα core and the CER in the next section.

3.6.3. H I Image

The bottom-left panel of figure 9 shows the CO image superimposed on the H I image taken from Cayatte et al. (1990). Note that the spatial resolution of the H I data (17″ × 13″) is much larger than the resolution of our CO data (2′0 × 1′8). The H I gas forms a ring-like structure, which is similar to the Hα image. The molecular CER is located at the central-east part of the H I ring.

— Figure 9 —

4. Discussion

The highest resolution CO map shows that six molecular blobs are likely to be the CER. There is a bright Hα core at the center of the CER. The existence of the CER is common and is sometimes found in spiral galaxies (e.g., Kono et al., 2003). The formation of the CER may be related to the dynamical condition, which we discuss in the following subsection. Moreover, we discuss the existence of molecular blobs and the bright Hα core accompanying the CER.

4.1. Formation of the CER

The velocity field (figure 7) and the PV diagram (figure 8) show the existence of a strong non-circular motion. Nakanishi (2004) showed that the two-dimensional orbits of the ISM of this galaxy are in fact oval. This non-circular motion implies that there is an asymmetric potential (bar structure). Although the optical image of NGC 4569 does not show a strong bar, the non-circular motion can be reproduced even by a weak-bar potential (e.g., Wada, Habe, 1992; Koda, Wada, 2002). The central gas dynamics is largely related to the radii of the inner Lindblad resonances (ILRs). Wada and Habe (1992) have shown that the gas forms a CER around ILRs. NGC 4569 might have ILRs and the CER has been formed as a result.

We compare the observational data with a Smoothed Particle Hydrodynamics (SPH) simulation of a gas disk in a bar potential. Figures 11 a, b, and c show snapshots of the gas distribution, and velocity field, and a PV diagram from model E of Koda and Wada (2002), respectively. We rotated the gas distribution and the velocity field so that their major axes are aligned with the horizontal axes of figures 11a and b using a position angle of 18° and an inclination of 63°. The major axis of the elliptical ring is assumed to be tilted counterclockwise by 31° on the plane of the galaxy disk (see subsection 3.3.2). There is a strong concentration of the gas on a central elliptical ring, and the gas is moving along the ring (figure 11a).

Figure 11b shows that the global velocity gradient is not parallel to the minor axis of the main disk, which implies that the gas does not circularly rotate. A PV diagram of the CER is shown in figure 11c, which shows forbidden velocity components as blue-shifted components in the left-hand side and red-shifted components in the right-hand side. The PV diagram is similar to a parallelogram. As shown in figure 8, the gas in the CER moves along this parallelogram.

Corresponding figures are presented in the right-hand side of figure 11; figures 11A, B, and C are the gas distribution, velocity field, and PV diagram obtained from observations, respectively.

The observed features for NGC 4569 are well reproduced by the SPH simulation; the observed ring structure in the higher resolution map (figure 11A) is similar to the elliptical ring of figure 11a. The S-shaped twists in the observed velocity field (figure 11B) are similar to that of the model (figure 11b). The parallelogram-like feature seen in the observed PV diagram (figure 11C) is also reproduced by the model (figure 11c).

In the next subsection, we discuss the gaseous self-gravity and the formation of large molecular blobs.

— Figure 11 —

4.2. Large Molecular Blobs and Central Starburst

Wada and Habe (1992) discussed that the CER fragments and collapses due to the self-gravitational instability of gas when the ratio of the gas mass to the stellar mass is larger than 10%. They described the process of decay of the CER as follows: (1) If the CER is dense enough, it fragments and collapses into blobs due to the self-gravity. (2) Then, these gas blobs collide with each other. Kinetic energy is dissipated due to the collisions. (3) Massive blobs are formed by accumulating smaller blobs, losing the kinetic energies. (4) Consequently, the large blobs fall into the center.

The observed results are likely to support this scenario. First, the CER and non-circular motion are consistent with the gas distribution and velocity field caused under a weak bar potential in numerical hydrodynamic simulations. Second, the large molecular blobs observed in this galaxy are also found in simulations. The largest blob A is the closest to the galactic center, which can be understood by the scenario: small blobs grow into a larger one while losing the kinetic energies due to collisions; then, the larger blob falls into the central region because of the loss of kinetic energy. Wada and Habe (1992) discussed that a gravitational instability occurs when the gas-to-stellar mass ratio within a radius is greater than 10%. This condition is satisfied in this galaxy as follows. The rotational velocity is ∼ 130 km s⁻¹ at the radius of 20″, adopting an inclination angle of 63° (see figure 8). The dynamical mass within 20″ is calculated to be 6.1 × 10⁶ M⊙. Using the equation (1), the gaseous mass within 20″ was 1.1 × 10⁶ M⊙. The gas-to-stellar mass ratio reaches 18%. Therefore, the self-gravity of the gas is important and a self-gravitational instability can occur.

Thus, the observable results support the scenario that the gas becomes clumpy due to its self-gravity, accumulated into the center, and is leading to the central starburst (Wada, Habe, 1992). The central bright Hα core might be caused by the gravitational instability of the CER and consequent gas inflow.
5. Summary

We observed the central region of NGC 4569 in the $^{12}$CO ($J = 1-0$) line using NMA. The high-resolution ($1''.8 - 2''.0$) CO image showed that the six blobs form the CER with a radius of 720 pc. The velocity field and PV diagram of the CER show the presence of strong non-circular motions, which may result from a central weak bar. Compared with the H$\alpha$ image, we found that the CER is located in the H$\alpha$ bright central core. The gas-to-stellar mass ratio within a radius of 20$''$ is 18%.

The results, i.e. (1) the blobs within the CER, (2) non-circular motions, (3) the coincidence of the CER and the bright H$\alpha$ core, and (4) the large gas-to-stellar mass fraction, support the scenario of gaseous inflow driven by a bar potential and the gaseous self-gravity (Wada, Habe, 1992).

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Table 1. Properties of NGC 4569.

| Parameter       | Value     | Reference |
|-----------------|-----------|-----------|
| Morphology      | SAB(rs)ab | 1         |
| Position        |           | 2         |
| RA(J2000)       | 12$^h$36$^m$49$^s$.8 | 1 |
| Dec(J2000)      | +13$^o$09$'$46$''$.3 | 1 |
| Total B Magnitude | 10.26 mag | 1 |
| Systemic velocity | −235 km s$^{-1}$ | 1 |
| Assumed distance | 16.1 Mpc | 3 |
| Inclination angle | 63$^o$ | 4 |
| Position angle  | 18$^o$ | 4 |

*(1) RC3 (de Vaucouleurs et al. 1991); (2) Jarrett et al. (2003); (3) Ferrarese et al. (1996); (4) Nakanishi (2004).

Table 2. Observation Parameters.

| Parameter                      | Value     |
|--------------------------------|-----------|
| Observed center frequency (GHz) | 115.286574 |
| Array configurations           | AB, C, & D |
| Observing field center         |           |
| RA(J2000)                      | 12$^h$36$^m$49$^s$.82 |
| Dec(J2000)                     | +13$^o$09$'$45$''$.8 |
| Frequency channels             | 256       |
| Total bandwidth (MHz)          | 512       |
| Velocity coverage (km s$^{-1}$) | 1382      |
| Velocity resolution (km s$^{-1}$) | 10.4    |
| Amplitude and phase calibrator | 3C 273    |
| Primary beam ($''$)            | 65        |

Fig. 1. STScI Digitized Sky Survey (DSS) B-band image of NGC 4569. The central square indicates regions of CO maps ($1'' \times 1''$), which are shown in figure 4.
Table 3. Parameters of Maps.

| Weighting function | Beam FWHM (″) | P.A. (°) | Velocity Resolution (km s\(^{-1}\)) | Sampling (km s\(^{-1}\)) | r.m.s. noise σ (mJy beam\(^{-1}\)) | \(T_b\) for 1 Jy beam\(^{-1}\) (K) |
|--------------------|-------------|--------|-------------------------------|-----------------|-----------------|-------------------------------|
| natural            | 4.5 × 3.1   | 146    | 10.4                         | 10.4             | 23              | 6.59                          |
| uniform            | 2.0 × 1.8   | 104    | 20.8                         | 10.4             | 34              | 25.5                          |

Table 4. Parameters of CER.

| Central position | Radius major (pc) | Axial ratio | Position angle |
|------------------|-------------------|-------------|----------------|
| On the sky       | 720               | 0.24        | 31° (from north on the sky) |
| Face-on view     | 280               | 0.39        | 31° (from major axis face-on) |

Table 5. Parameters of velocity fields.

| Resolution | Smoothing width (″) | Velocity range | Threshold |
|------------|--------------------|----------------|----------|
| low        | 1.25               | −437.8 −42.6   | 0.76     |
| high       | 0.25               | −422.3 −58.2   | 0.87     |

Table 6. Parameters of blobs.

| Name | Peak Position RA(J2000) Dec(J2000) | Peak intensity (K km s\(^{-1}\)) | Mass \(^{*}\) \((M_\odot)\) | Velocity (km s\(^{-1}\)) |
|------|-----------------------------------|-------------------------------|-------------------|-----------------|
| A    | 12\(^{h}\) 36\(^{m}\) 49\(^{s}\) 13° 09′ 42″/9 | 805                           | 1.39 × 10\(^{7}\)\(^{*}\) (1) | −242            |
| B    | 12\(^{h}\) 36\(^{m}\) 49\(^{s}\) 13° 09′ 47″/4 | 481                           | 2.82 × 10\(^{7}\)\(^{*}\) (1) | −242            |
| C    | 12\(^{h}\) 36\(^{m}\) 50\(^{s}\) 13° 09′ 52″/6 | 459                           | 2.29 × 10\(^{7}\)\(^{*}\) (1) | −149            |
| D    | 12\(^{h}\) 36\(^{m}\) 50\(^{s}\) 13° 09′ 52″/6 | 317                           | 5.44 × 10\(^{6}\)\(^{*}\) (2) | −122            |
| E    | 12\(^{h}\) 36\(^{m}\) 49\(^{s}\) 13° 09′ 54″/2 | 432                           | 3.40 × 10\(^{7}\)\(^{*}\) (1) | −108            |
| F    | 12\(^{h}\) 36\(^{m}\) 49\(^{s}\) 13° 09′ 49″/1 | 335                           | 6.03 × 10\(^{6}\)\(^{*}\) (2) | −158            |

\(^{*}\) Threshold intensity is taken to be 360 \(^{*}\) (1) and 300 \(^{*}\) (2) K km s\(^{-1}\).

Fig. 2. CO spectra at the observing centers of the low- and high-resolution maps, corrected for primary beam attenuation and convoluted with a Gaussian profile (FWHM = 16″). Left: Spectrum of the low-resolution map. Right: Spectrum of the high-resolution map. Because of large missing flux in the high-resolution map, the right spectrum is weaker than the left one.
Fig. 3. CO channel maps of the central 35'' obtained with uniform weighting. The first channel at the top-left corner corresponds to a radial velocity of $-422.3$ km s$^{-1}$, and the last one at the bottom right corner corresponds to $-58.2$ km s$^{-1}$. The contour levels are 1.5, 3, 6 $\sigma$ ($\sigma = 34$ mJy beam$^{-1}$).
Fig. 4. CO velocity-integrated intensity map. Left panel: CO map obtained with natural weighting. The contour levels are 60, 120, 180, 240, 300, 360, 420, 480, 540, and 600 K km s$^{-1}$. Right panel: CO map obtained with uniform weighting. The contour levels are 120, 180, 240, 300, 360, 420, 480, 540, and 600 K km s$^{-1}$. 
Fig. 5. Radial profile of the $\text{H}_2$ molecular gas distribution. The vertical axis is logarithmic scale. The fitted line denotes $\Sigma [M_\odot \text{pc}^{-2}] = 670 \exp (-R/0.58(\text{kpc}))$.

Fig. 6. Elliptical fitting of the CER. The thick line shows the best-fitted ellipse, whose center is indicated by asterisk symbol. The black cross shows the central position determined by 2MASS image (Jarrett et al. 2003). Six CO blobs are indicated by figures of 'A', 'B', 'C', 'D', 'E', and 'F'. Their peak positions are indicated by white crosses. Left: On the sky. Right: Face-on view.
Fig. 7. Velocity fields obtained with natural weighting (left) and with pure uniform weighting (right). Contour levels are $-335, -310, -285, -260, -235, -210, -185, -160,$ and $-135$ km s$^{-1}$. The white line indicates $-235$ km s$^{-1}$. 
Fig. 8. PV diagrams along the major axis made from the low-resolution cube. The central panel is a low-resolution CO image, which was rotated by 72° counter-clockwise so that its major axis is horizontal. The top panel was obtained by slicing the cube along the major axis, which is shown as the central thick line in the central panel. The bottom panel shows an averaged PV diagram over 15′′ width, which is shown by two dashed lines in the central panel.
Fig. 9. CO image with uniform weighting superimposed on images with other wavelengths. The square box with the dashed line denote the central 1′ × 1′ in each box. Top-left: CO map (contour) and R-band image (gray), which is taken from Koopmann et al. (2001). Top-right: CO map (contour) and Hα image (gray), which is taken from Koopmann et al. (2001). Bottom-left: CO map (contour) and H i image (gray), which is taken from Cayatte et al. (1990).
Fig. 10. Magnified images of the central regions of figure 9. Left panel: The central region of the CO (contour) and $R$-band image (gray), which is the top-left panel of figure 9, but with a different contrast. Right panel: The central region of the CO (contour) and H$\alpha$-band image (gray), which is the top-right panel of figure 9.
Fig. 11. Comparisons of the SPH simulation presented by Koda and Wada (2002) and the observed data. Left-hand-side images are results of an SPH simulation; (a) Gas distribution, (b) Velocity field, and (c) Position–velocity diagram. Right-hand-side images are observational data; (A) High resolution CO image rotated by 72° counterclockwise, (B) Low-resolution velocity field rotated like (A), and (C) Position–velocity diagram.