PASJ: Publ. Astron. Soc. Japan , 1–**??**,

Virgo High-Resolution CO Survey VII. – High Density Molecular Nuclei –

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(Received 2007 0; accepted 2007 0)

Abstract

In our high-resolution CO survey of fourteen Virgo normal spirals, we noticed four galaxies (NGC 4192, NGC 4419, NGC 4535, and NGC 4536), which showed centrally peaked high-density molecular nuclei. In order to investigate finer structures, we have applied a uniform-weighting analysis to the intereferometer data, and otbained the highest resolution CO-line maps with synthesized beamsizes of 1 to $2''$ for the central regions of these galaxies. These high resolution maps show that the central peaks are still not resolved, and the intensities are as high as ~ 600 K km^{-1}. This corresponds to H_2 column density of $6\times 10^{22} H_2 cm^{-2}$, and to a surface gas mass density of $1.4\times 10^3 M_\odot$ pc^{-2}. These values are comparable to that found for the molecular nucleus of NGC 3079 with the highest molecular density ever observed. The nuclear gas disks appear to be stabilized by high-velocity differential rotation due to central massive cores. Star formation rates in the molecular nuclei are largely scattered around the usual Schmidt law by a factor of ten, suggesting that the molecular nuclei are either in a pre-starburst phase or in a starburst phase.

Key words: galaxies: spiral — galaxies: ISM — galaxies: structure — galaxies: Virgo cluster of — galaxies: nuclei — ISM: molecular gas

1. Introduction

The molecular gas in spiral galaxies is highly concentrated in the central ~ 1 kpc regions, composing nuclear molecular disks. Morphology of central molecular disks shows a variety. Some galaxies, including the Milky Way, have molecular rings, which are often associated with "twin peaks" (Kenney et al. 1992). On the other hand, many galaxies have a strong peak of molecular gas at their centers. Kenney et al. (1992) noticed a galaxy, NGC 3504, with a prominent peak of CO emission in the central kiloparsecs. The nuclear molecular disk was analyzed in detail in Kenney et al. (1993). About half of the 20 spiral galaxies observed in the NRO-OVRO survey showed a molecular peak at the center (Sakamoto et al. 1999a, b), and more cases were found in the BIMA SONG survey (Regan et al. 2001; Helfer et al. 2003). Garcia-Brillo et al. (2005) have studied molecular gas in the nuclei of four galaxies, among which NGC 4321 showed a strong molecular nucleus. They argued for the feeding mechanism by the gravitational torque in central 1 kpc regions. From the current studies, the morphology of central molecular disks appears to be classified into ring/twin-peak type, which is followed from the outer bar and/or spiral arms, and central peak (molecular nucleus) type, which show dense molecular peaks not resolved in the current observations.

Anomalously high density concentration of molecular gas in an extremely deep gravitational potential with very high-velocity rotation has been detected in NGC 3079 (Sofue et al. 2001; Koda et al 2002). In our Virgo CO line survey, we have noticed six galaxies with central peak morphology among the 14 observed galaxies, and some showed similar characteristics to that of NGC 3079. In figure 1, we reproduce the CO intensity maps of these six central peak galaxies, NGC 4192, NGC 4212, NGC 4419, NGC 4501, NGC 4535 and NGC 4536 from Paper I (Sofue et al. 2003a). However, a higher-resolution analysis of NGC 4501 revealed its twin-peak characteristics (Onodera et al. 2004). The other eight galaxies showed extended molecular gas distributions in the central regions, including a twin-peak type galaxy NGC 4303 (Koda and Sofue 2006) and a ring type NGC 4569 (Nakanishi et al. 2006).

The Virgo high-resolution CO survey with NMA (Nobeyama mm-wave Array) has been performed to obtain a homogeneous high angular- and spectral-resolution database for CO-bright spirals in the Virgo Cluster of galaxies in the ^{12}CO$(J=1-0)$ line at 115 GHz. In our series of papers we presented the results with angular resolutions of $\sim 3-5''$ for 14 galaxies by usual reduction (CLEAN) procedure with natural weighting for UV coverage (Sofue et al. 2003a, b, c (Papers I, II, III). In the present paper, we reanalyze the UV data of NGC 4192,

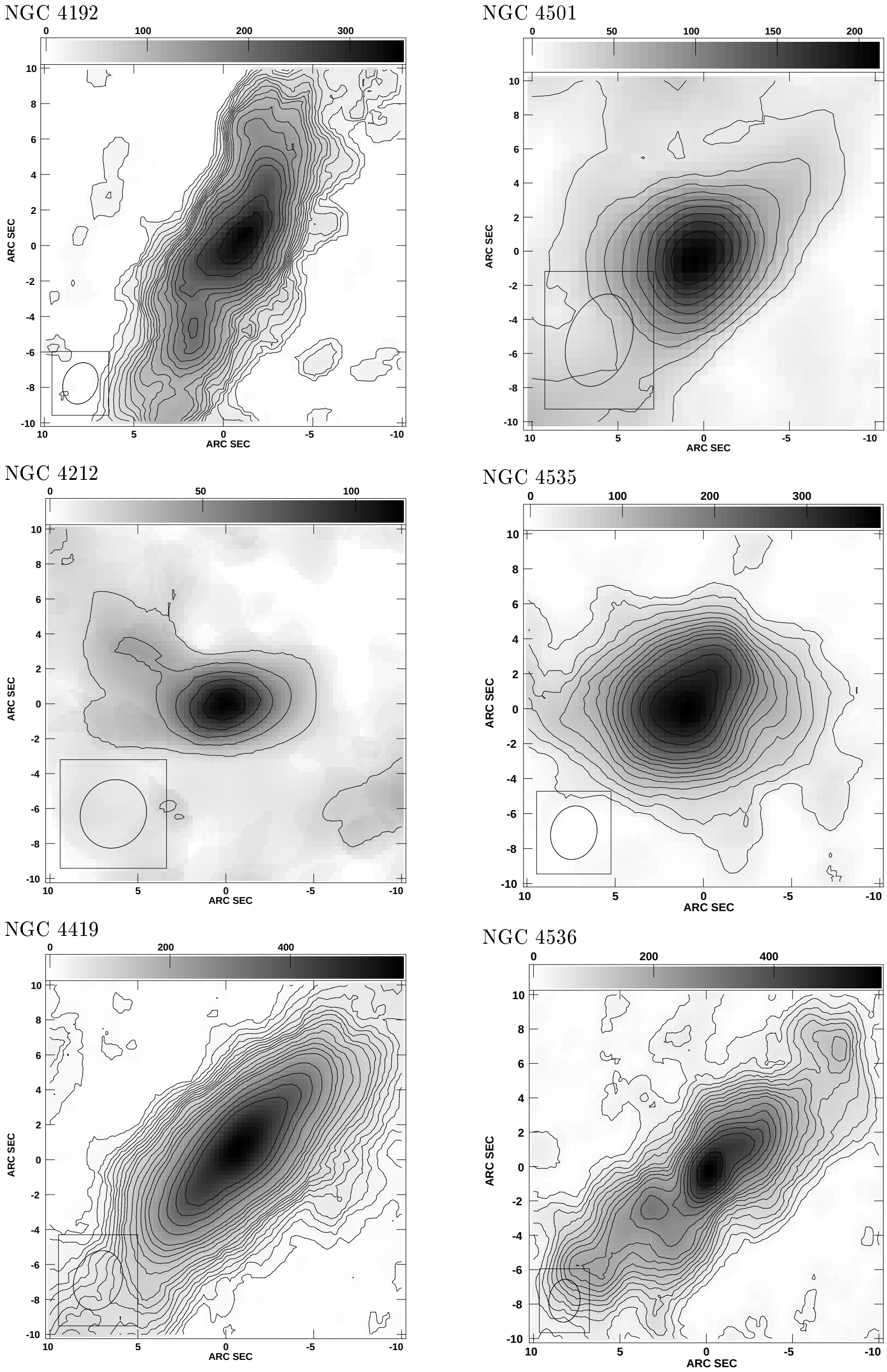

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Fig. 1. Fig. 1. Integrated CO intensity maps for the six centrally-peaked galaxies as found in the Virgo CO survey at intermediate resolutions of $2-4''$ (Sofue et al. 2003a).

NGC 4419, NGC 4535 and NGC 4536 by applying uniform weighting to their antenna spacings, in order to enhance peaky structures in the central regions. We do not include NGC 4212, which was observed only in C and D arrays, and threfore, without sufficient resolution.

We investigate the physical characteristics of centrally peaked molecular gas concentration, which we call the molecular nuclei, in comparison with the extremely dense molecular core found in NGC 3079, which exhibits the highest gas density among the galaxies so far observed at Nobeyama. We also discuss the Schmidt relation for these high-density molecular nuclei, and show that the correlation is largely scattered from the general relation, confirming the result of Komugi et al (2005) on the Schmidt law scatter in high densities. We also compare the molecular nuclei with the central molecular zone (CMZ) in the Milky Way center, and discuss the generallity of high molecular nuclei in normal spiral galaxies.

2. Uniform-weighting High-resolution CO-line Maps

2.1. *Reduction*

Details of the observations are described in Paper I (Sofue et al. 2003a). The raw data were calibrated using UVPROC-II, a first-stage reduction software package at NRO, and the data were Fourier-transformed using the NRAO Astronomical Image Processing System (AIPS). We CLEANed the data with uniform weighting functions, which provided maps with a synthesized beam size (FWHM) of $\sim 1-2$", which may be compared with those in Paper I of $\sim 3-5$". The distance to the Virgo galaxies is assumed to be 16.1 Mpc (Ferrarese et al. 1996), and therefore, $1''$ corresponds to 78 pc. Table 1 lists the four galaxies with their map-center positions and syntheized beam sizes. For comparison we also list the data and results for NGC 3079 as obtained by the same procedure applied to our earlier observations (Koda et al. 2002).

In figures 2 – 7 we show the obtained integrated CO intensity maps, namely moment 0 maps, by applying the AIPS task 'MOMNT' with threshold levels of 2 to 3 times the rms noise in the data cubes. The primary-beam correction has not been applied in these maps, because the displayed areas are the central $30''$ squared regions, where the primary-beam effect is less than 10% even near the map edges. The intensity scales in the maps are brightness temperature in K. Table 2 shows the peak CO intensities, as read from these intensity maps. Figures 2 – 7 also show intensity weighted velocity fields, or moment 1 maps, and position-velocity diagrams along the major axes, as well as channel maps for individual galaxies.

We describe the CO properties obtained from the present observations for individual galaxies.

2.2. *NGC 4192*

The galaxy is nearly edge on with an inclination angle of $i=74^\circ$. A dense molecular core is found near the center, which may be resoleved into three clumps aligning roughly along the major axis. The peak position of the brightest clump is slightly offset by $\sim 0''.6$ (47 pc) from the map center toward SW along the minor axis. The velocity field indicates that the kinematical center coincides with this clump. Since the brightest peak is located on the major axis defined by the CO line disk in the whole map area, we may take the true center to be at the peak position of this brightest clump. The apparent elongation of the central core in the minor axis direction depends on the SW clump, which may either a true off-plane structure from the nucleus, or a clump in the nuclear disk or spiral arms in the farside (SW side) of the galaxy. The large-scale molecular disk comprises a sharp ridge along the major axis of the galaxy, and is superposed by several clumps. This ridge of molecular disk coincides with dark lanes in optical photographs (Paper I).

2.3. *NGC 4419*

A high concentration of CO gas is found in the center, while its peak is slightly offset from the map center along the major axis toward NW by $0''.4''$ (30 pc). This molecular core is surrounded by a smooth, bright ridge, comprising a nuclear molecular disk. The velocity field and PV diagram show a rigid-body like rotation of the nuclear disk. The morpholoty is similar to NGC 3079, while the rotation velocity of the central core is much slower.

2.4. *NGC 4535*

The molecular gas shows a strong concentration in the central region of $\sim 6''$ radius. This galaxy is a typical central peak type. Offset bars are extending from the central disk toward the NE and SW, coinciding with the optical dark lanes in the bar. The velocity field shows a usual spider diagram with the zero velocity node at position angle of 90°, coinciding with the optical minor axis. However, the CO arms along the dark lanes show some non-circular streaming velocity, indicating inflow along the arms. The PV diagram shows a sharply rising, but rigid body-like behavior within the central molecular disk.

2.5. *NGC 4536*

This is also a typical central peak type galaxy with the molecular gas being concentrated in the nuclear disk of $\sim 10''$ radius and an unresolved compact core exists at the nucleus. The molecular gas morphology is most similar to that of NGC 3079 among the listed galaxies. The velocity field shows a spider diagram, and the PV diagram indicates that the rotation velocity rises to 200 km s^{-1} within the central $2''$. There appears no strong non-circular streaming motion. The steep rise and high velocity rotation is also similar to NGC 3079.

3. Discussion

3.1. *Properties of the molecular nuclei*

In our fourteen noraml spiral galaxies in the Virgo CO survey we found several galaxies showing central peaks of high-density molecular gas, which we call the molecular nuclei: NGC 4192 (SAB(s)ab)), NGC 4212 (SAc), NGC 4419 (SB(s)a), NGC 4501 (SA(rs)b), NGC 4535 (SAB(s)c)

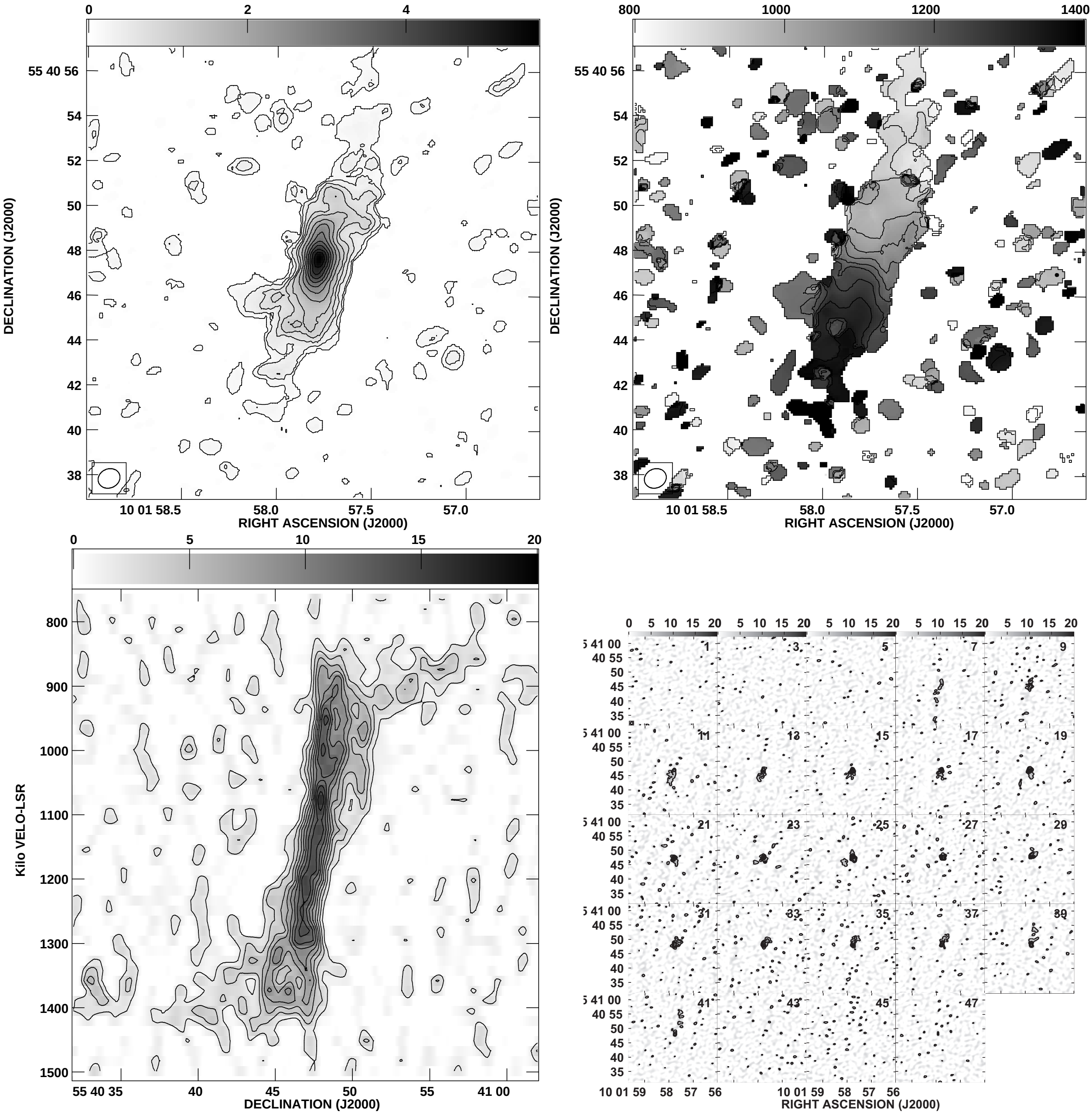

Fig. 2. (a) Uniform weighting integrated intensity maps in the CO line, (b) velocity fields, (c) pv diagrams, and (d) channel maps for NGC 3079. Intensity contour levels are 20 × (1, 2, ..., 10, 12, ... 20, 25, ... 40) K km s^{-1}.

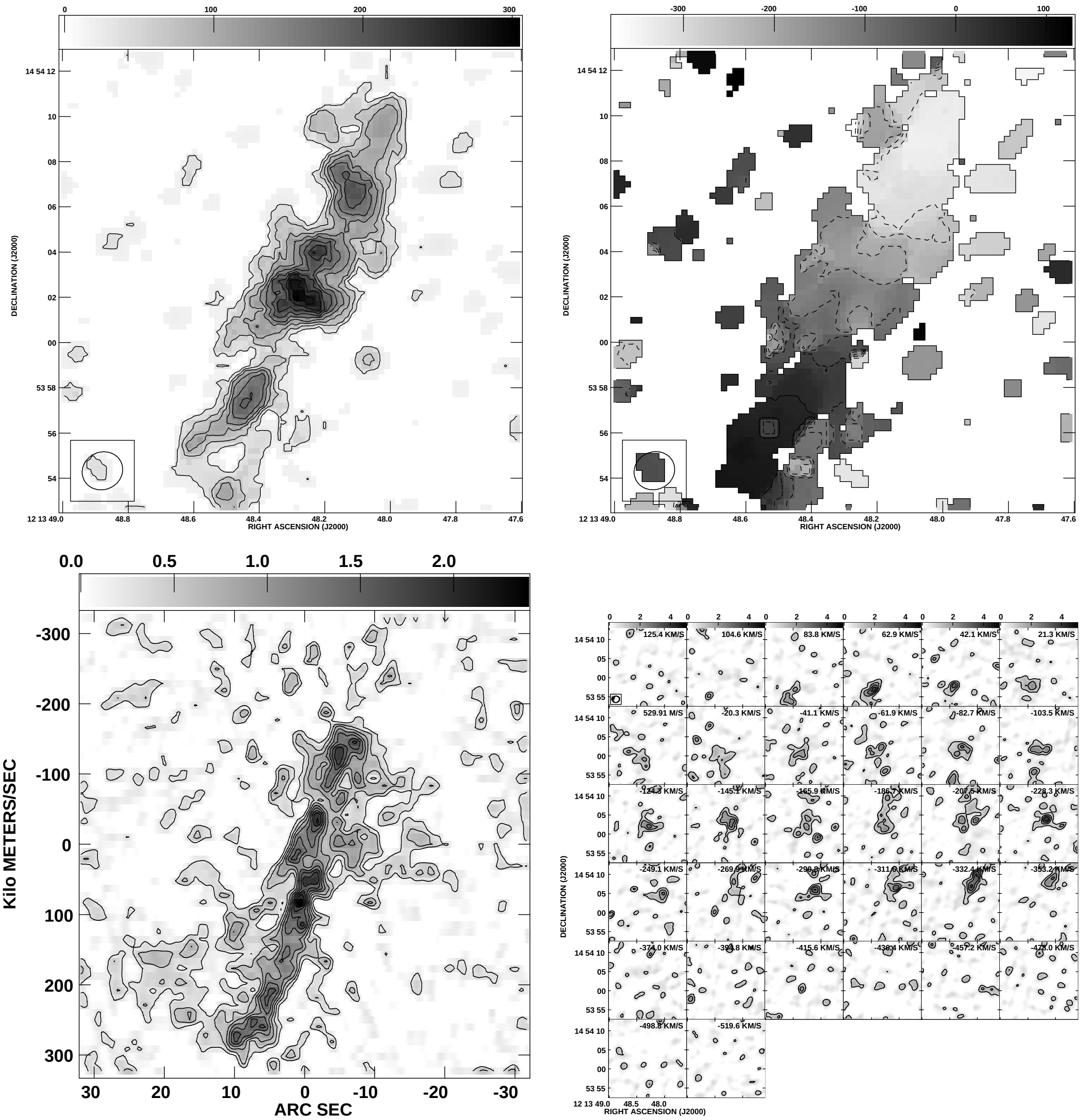

Fig. 3. Same as Fig. 2 but for NGC 4192

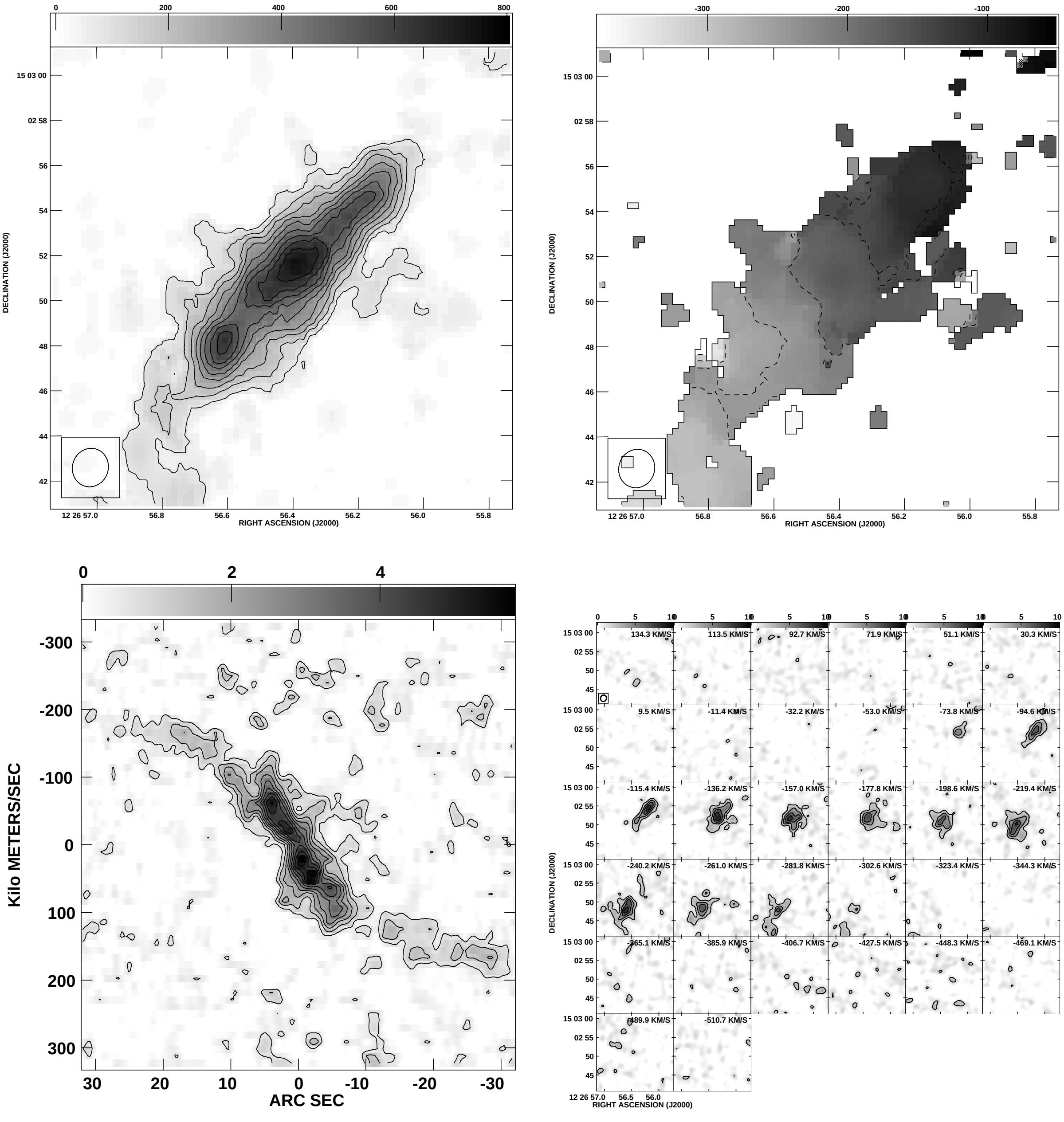

Fig. 4. Same as Fig. 2 but for NGC 4419

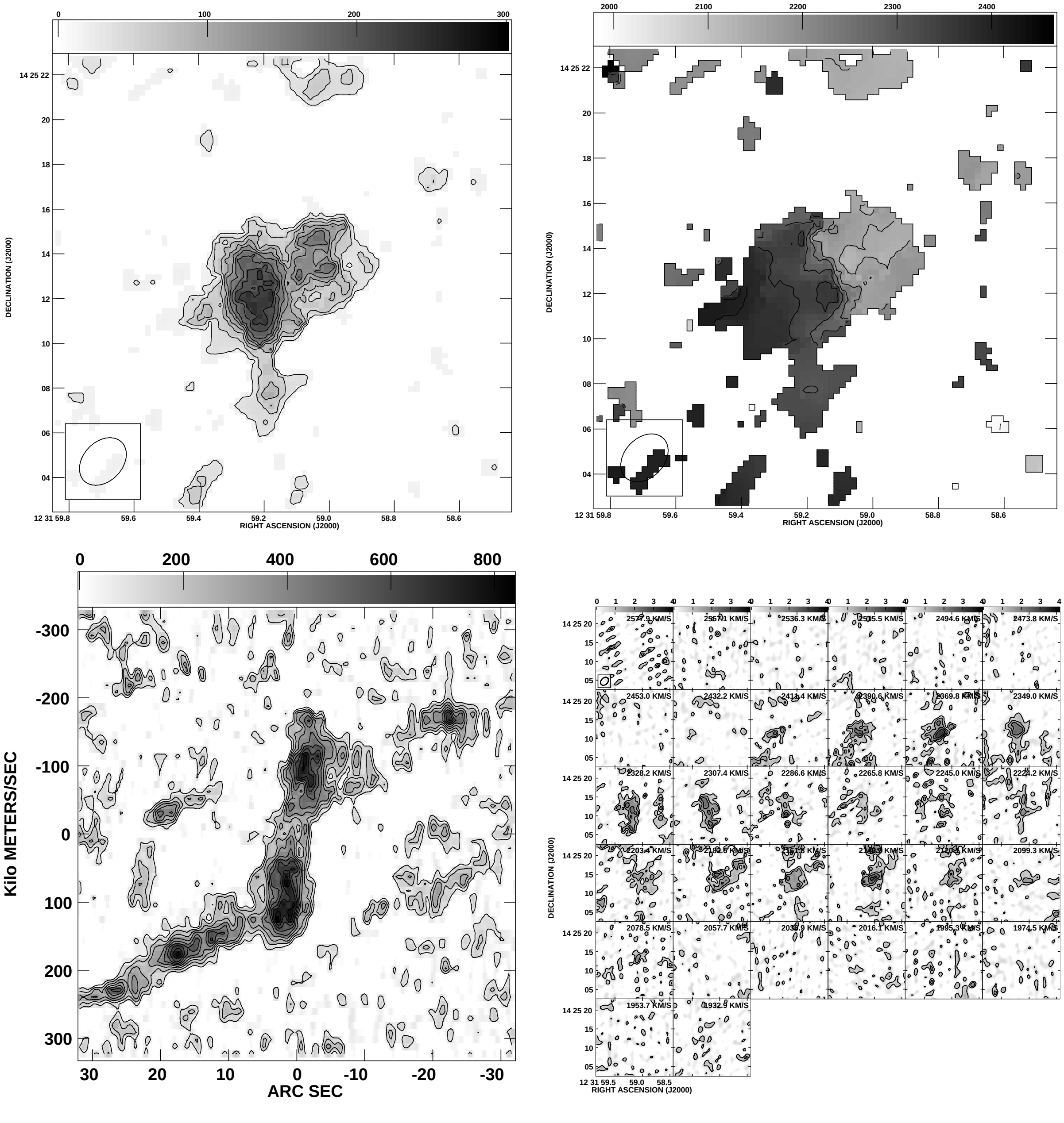

Fig. 5. Same as Fig. 2 but for NGC 4501

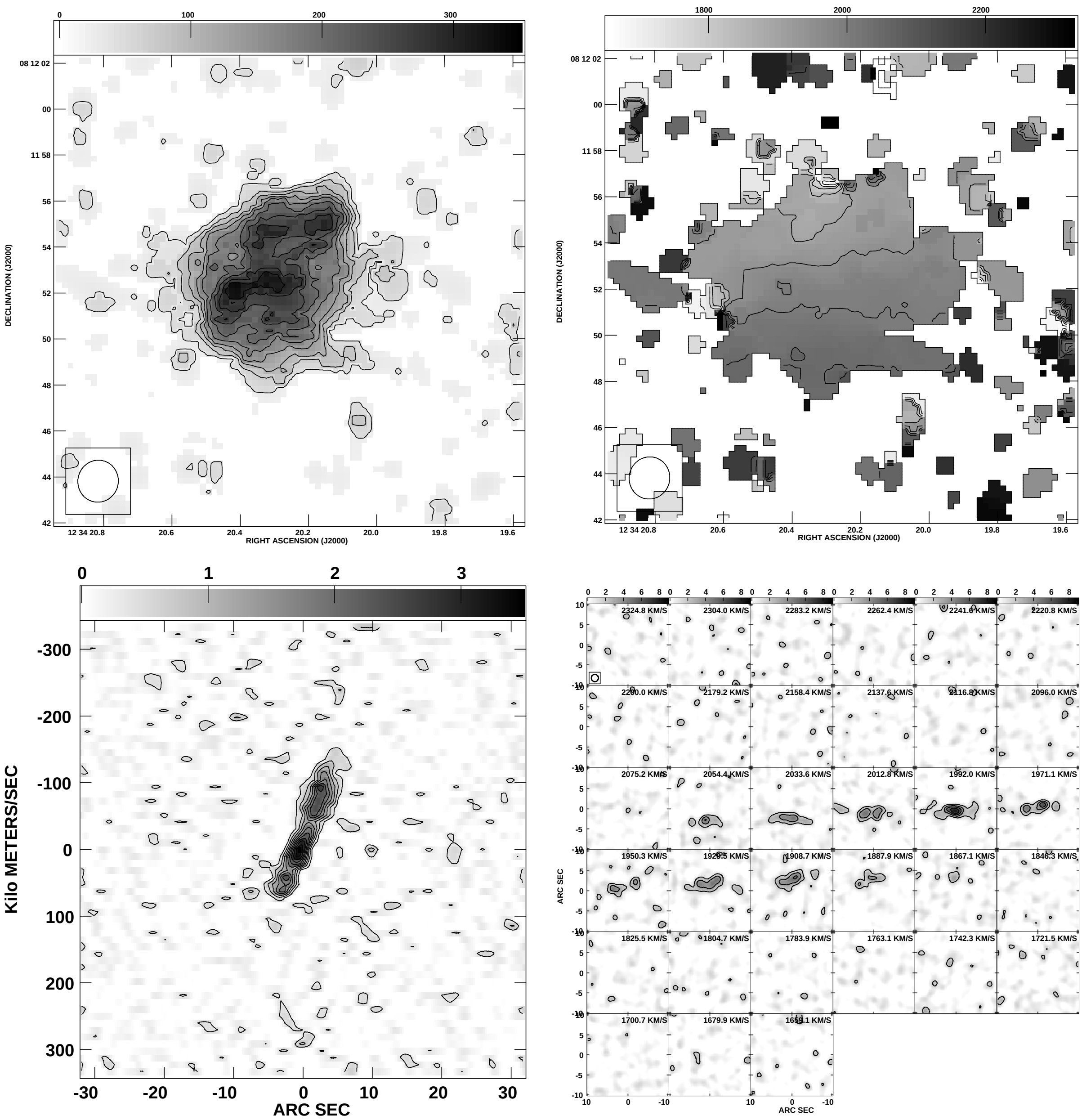

Fig. 6. Same as Fig. 2 but for NGC 4535

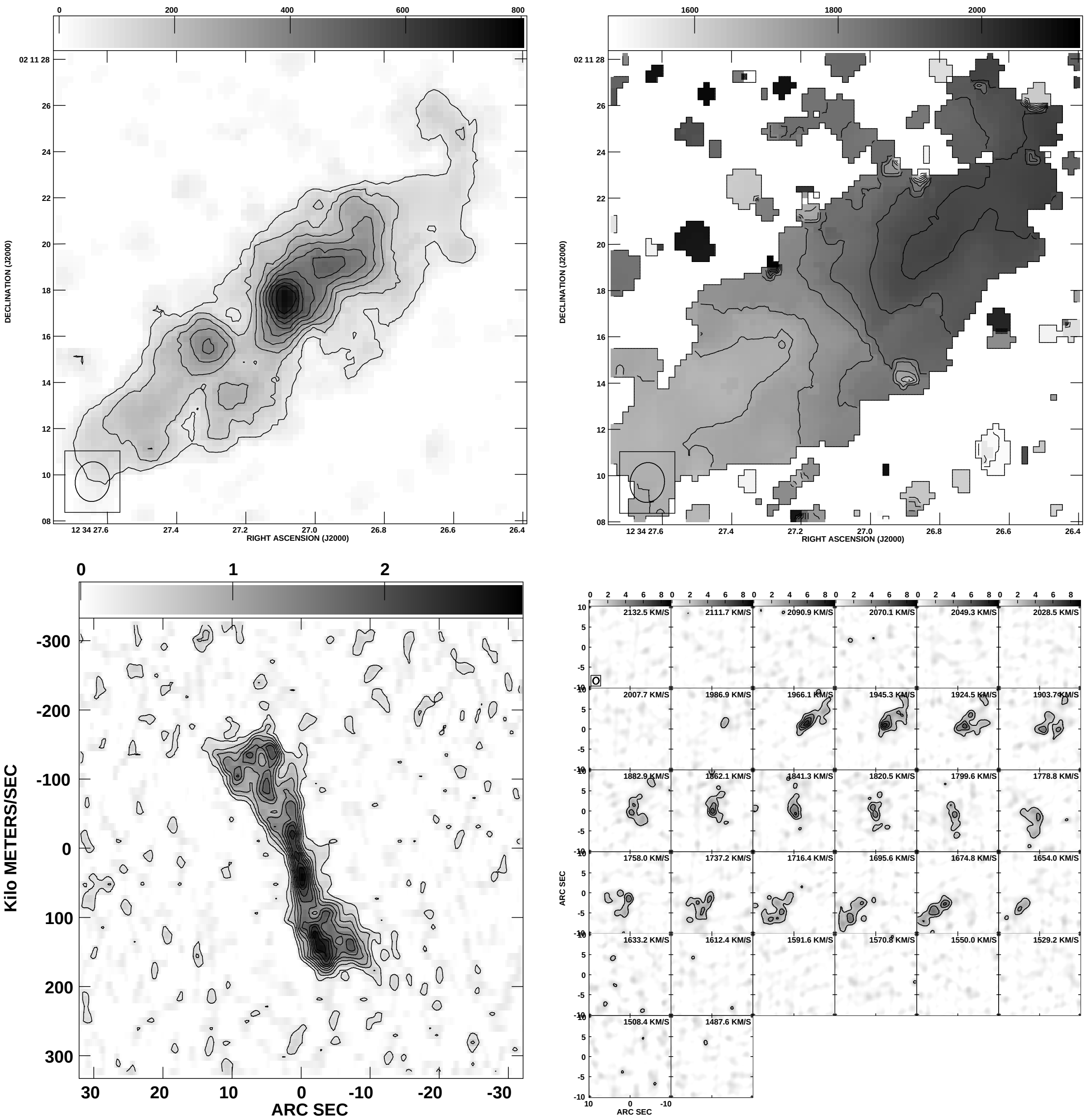

Fig. 7. Same as Fig. 2 but for NGC 4536

Table 1. S-peak galaxies

Galaxy	Map Center (2000) RA[h m s]	Dec[° ′ ″]	Synthesized Beam [″×″]
NGC 3079	10 01 57.81	55 40 47.1	1.00×0.84
NGC 4192	12 13 48.30	14 54 03.0	1.82×1.65
NGC 4419	12 26 56.43	15 02 51.2	1.72×1.59
NGC 4535	12 34 20.26	08 11 52.3	1.83×1.76
NGC 4536	12 34 27.07	02 11 18.4	1.73×1.48

Table 2. Peak CO Brightness Temperatures and Intensities

Galaxy	$T_{\rm b,peak}$ (K)	$I_{\rm CO,peak}$ (K km s^{-1})	Inclination i (degree)	$I_{\rm CO,peak}\cos i$ (K km s^{-1})	SMD, Σ ($M_\odot$pc^{-2})
NGC 3079	19.0	5660	85	493	1130
NGC 4192	4.0	303	74	85	194
NGC 4419	9.4	744	67	290	662
NGC 4535	8.3	337	43	246	562
NGC 4536	8.5	762	67	297	678
Milky Way Center†				~ 100	~ 230

† Calculated from Oka et al.' (1998) figure 2 for the same conversion factor.

and NGC 4536 (SAB(rs)bc). Among these, NGC 4212 was observed only in C+D arrays, so that the resolution was not sufficient for a detailed study. NGC 4501 was found to exhibit plateau-like intensity distribution in the center, but has no distingushied central peak. We have, thus, recognized the four galaxies, NGC 4192, 4419, 4535 and 4536 as molecular-nucleus galaxies in the present resolution, and called them molecular nuclei. Their morphology shows similar characteristics to the high-density molecular core of NGC 3079.

The face-on CO intensity for the molecular nucleiis

$$I_{\rm CO}\cos i \sim 3\times 10^2 \ {\rm K\ km\ s^{-1}} \quad (1)$$

(table 2: NGC 4419, NGC 4535, NGC 4536). For a conversion factor of

$$X_{\rm CO} \sim 1\times 10^{20} \ {\rm H_2[K\ km\ s^{-1}]^{-1}} \quad (2)$$

for the central regions of spiral galaxies (Arimoto et al. 1996), we have column density of the molecular gas as seen face-on to be

$$N_{\rm H_2} \sim 3\times 10^{22} \ {\rm H_2cm^{-3}}. \quad (3)$$

This corresponds to a surface mass density of

$$\Sigma \sim 6\times 10^2 M_\odot {\rm pc^{-2}} \quad (4)$$

for an H_2-to-total gas mass ratio of 0.7. If the disk thickness of molecular nucleus is a few tens of parsecs, the spatial gas density is on the order of

$$n_{\rm H_2} \sim 3\times 10^2 {\rm H_2cm^{-3}}. \quad (5)$$

These values for the molecular gas surface mass density are comparable to those obtained for the molecular nuclei in the galaxies studied by Garcia-Brillo et al. (2005): They obtained $\Sigma \sim 10^3 M_\odot{\rm pc^{-2}}$ for a conversion factor of $X_{\rm CO} = 2.2\times 10^{20}{\rm H_2[K\ km\ s^{-1}]^{-1}}$, and, therefore, $\Sigma \sim 500 M_\odot{\rm pc^{-2}}$ for the same conversion factor as in this paper.

It is interesting to note that the molecular gas SMD in these nuclei is comparable to that of a single giant molecular cloud in the Galactic disk for a typical diameter of ~ 50 pc and mass $\sim 10^6 M_\odot$. Namely, the molecular nuclei are the regions where the galactic disk of radius $\sim 100-200$ pc is filled by molecular gas with comparable density to that of a giant molecular cloud. Such a coherently high-density disk would be a region ready for starburst, while its origin and mechanism to concentrae the gas into this small area is the major subjet to be solved for discussing the triggering mechanism of the starburst.

3.2. High-velocity rotation, stability of molecular clouds, and feeding of molecular nuclei

The molecular gas in galactic disks are generally accreted by galactic shocks along bars and/or oval distortion of disk potentials, resulting in the formation of a molecular ring of a few hundred pc radius around the central round potential. Mode-2 asymmetry of the inflow such as due to a bar may cause two-peaked concentration of gas on the ring. However, a further inward transport of gas inside the circum-nuclear rings has been the major subject in understanding the feeding problem of active galactic nuclei and triggering mechanism of starburst.

Garcia-Brillo et al (2005) have extensively discussed the feeding mechanism of molecular gas into the central ~ 100 pc disk by the gravitational torque, where rotation velocity shear plays an essential role. In the decade, high-accuracy central rotation curves have been derived for many galaxies, which indicate strong differential rotation in the central few hundre pc (Rubin et al. 1999; Bertola et al. 1998; Funes et al. 2002; Sofue and Rubin 2001). In this paper we also obtained high-resolution PV diagrams for the molecular nuclei of the Virgo galaxies. From these PV diagrams the dynamical mass within about 100 pc of these galaxies is calculated to be on the order of $\sim 10^9 M_\odot$, showing that the galaxies nest massive cores. The rotation periods and epicyclic frequencies are as short as $\sim 10^6$ y, which is comparable to the Jeans time of a typical giant molecular cloud. Therefore, the high dynamical mass and short rotation period can stabilize the molecular clouds from fragmentation, surpressing star formation, and assist effective feeding of the gas into the nuclei.

The Toomre's Q parameter has been often used to discuss the stability of nuclear gas disks (Kenney et al. 1991, 1993; Jogee et al.2005). The Q value is defined by

$$Q = \Sigma_{\rm c}/\Sigma, \tag{6}$$

where $\Sigma_{\rm c} = \kappa c_v/\pi G$ is the critical dynamical surface mass density (SMD), Σ is the surface mass density of gas, κ is the epicyclic freqeuncy approximately twice the rotation frequency as read from the position-velocity diagrams, and c_v is the velocity dispersion of the gas which is on the order of $c_v \sim 30$ km s^{-1} as a typical value from the PV diagrams some hundred pc away from the nuclei (figures 2-7). Then, we have the critical value for the surface mass density to be on the order of

$$\Sigma_{\rm c} \sim 4 \times 10^3 M_\odot {\rm pc}^{-2}. \tag{7}$$

This may be compared with the molecular gas SMD of $\Sigma \sim 6 \times 10^2 M_\odot {\rm pc}^{-2}$ (table 2). Then, we obtain Q values as large as $Q \sim 7$ for NGC 4419, 4535 and 4536. It is still as large as $Q \sim 4$ for the extremely dense molecular nucleus of NGC 3079. The molecular nuclei are thus gravitationally stable.

3.3. Large scatter in the Schmidt law for the molecular nuclei

It is expected that the star formation in the molecular nuclei would be suppressed prior to star formation, while after bursting the star formation becomes very active. Such situation may be represented by large scatter of star formation efficiency, or a scatter in the Schmidt law in the molecular nuclei. The Schmidt law as expressed by

$$SFR \propto SMD^N \tag{8}$$

has been studied extensively in disk galaxies. The index of $N = 1.4$ has been derived by Kennicutt (1998), and $N = 1.0$ by Nishiyama & Nakai(2001) and other authors (e.g., Wong & Blitz 2002, Komugi et al. 2005, Kennicutt et al. 2007). Kennicut (1998) showed a tight correlation even for starburst galaxies with high molecular densities, while Komugi et al (2005) suggested a larger scatter.

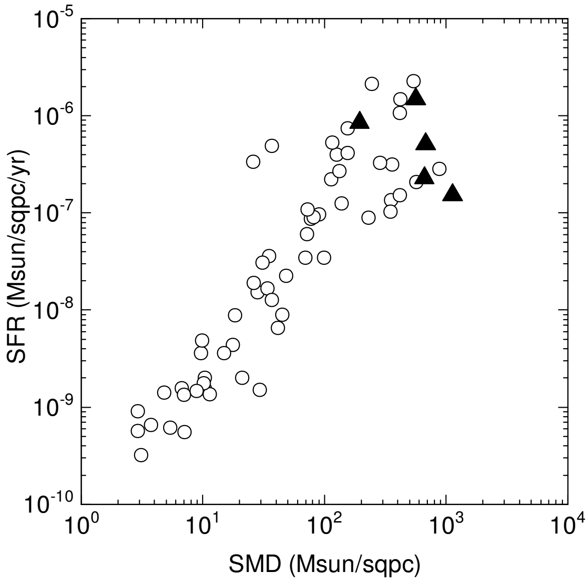

Fig. 8. The Schmidt law for spiral galaxies (open circles) from Komugi et al. (2005), where the conversion factor has been modified in the central 2 kpc as in the text. The molecular nuclei studied in this paper are plotted by triangles. The surface mass densities are corrected for the inclination angle of galaxy disk.

Figure 8 shows the Schmidt law for our sample (triangles). The open circles are taken from the study of normal galaxies and high-density molecular regions from Komugi et.al. (2005). The plot is best-fitted with a line of slope 1.36. The calculation of SFR was conducted using the following formulation (Kennicutt 1998):

$$SFR(M_\odot {\rm pc}^{-2}{\rm yr}^{-1}) = 7.9 \times 10^{-42} \frac{L({\rm H}\alpha)}{S} ({\rm erg\ s}^{-1}{\rm pc}^{-2}) \tag{9}$$

$$\Sigma(M_\odot {\rm pc}^{-2}) = 2 m_{\rm H}\ X_{\rm CO} I_{\rm CO} \times 1.64. \tag{10}$$

Here, S is the surface area subtended by the telescope beam, to convert values into surface densities. The $H\alpha$ data was taken from spectroscopic surveys by Ho et al. (1997). SMD was calculated using a CO to H_2 conversion factor of $X_{\rm CO} = 1.0 \times 10^{-20} {\rm H_2}[{\rm K\ km\ s}^{-1}]^{-1}$ for the central 2 kpc, and $X_{\rm CO} = 2.0 \times 10^{-20}$ for regions outside this radius. Here, $m_{\rm H}$ is the hydrogen mass, $X_{\rm CO} I_{\rm CO}$ gives the number density of Hydrogen molecules per cubic centimeter, and 1.64 accounts for the metallicity. The values have been corrected for inclination.

Although the Schmidt law has been thought to break down in local areas with scales less than one kpc, we see from figure 8 that the law generally holds even with a resolution corresponding to less than 100 pc, at least for those with SMD up to $10^2 M_\odot \mathrm{pc}^{-2}\mathrm{y}^{-1}$. The correlation has been found for resolved star forming regions and clouds in M51 (Kennicut et al. 2007). This gives rise to the possibility that even in the central regions of galaxies, where physical properties, such as the rotation period and magnetic fields, are different from surrounding disk regions, the Schmidt law still holds, controled by a general mechanism.

Although the Schmidt law, thus, generally holds in any circumstances in galaxies, it is also noticed that it has a lager scatter in some particular regions. Komugi et al. (2005) extensively studied the Schmidt law at high gas densities, and showed that the law is scattered by a factor of ten, much larger than that for normal disk galaxies. They also noticed two fold sequences according to the gas density. In figure 8, there are several galaxies which are "positively" deviated from the normal Schmidt law, including two whose SFE is closer to that for starburst galaxies. The star forming efficiency (SFE) varies drastically in the sense that the SFE is either much lower than that for normal disks, or higher. There are several galaxies whose SFE is anomoulasly lower than the normal Shmidt law.

NGC3079 is the most typical case which shows negatively deviated SFE from the general law, in the sense that the SFR is by an order of magnitude less than what is expected from the SMD of molecular gas. Alternatively SMD is an order of magnitude greater than what is expected from the SFR. NGC 3079 may be classified as a starburst because of its bipolar outbursting features in radio continuum, Hα and X-rays (Cecil et al. 2001, 2002; Sofue and Vogler 2001). Nevertheless, the SFE is negatively deviated from the Schmidt law. This implies that the star formation has been suppressed, but it could occur soon so that the galaxy may 'catch' up with the Schmidt Law. Hence, NGC 3079 is a galaxy with anomalously low SFE for its dense molecular nuclei, while its SFR is sufficiently high as a starburst.

Therefore, starburst is not a matter of enhanced SFE, but has been defined by absolute SFR. Alternativey, if starburst should be defined by its anomalously high SFE, such galaxies like N3079 with extremely high gas density may not be categorized as starburst. We may remind that the surface mass density of the molecular gas toward the starbursting 200 pc molecular ring in the typical starburst galaxy M82 is only $\sim 500 M_\odot \mathrm{pc}^{-2}$ for the same conversion factor as here (Nakai et al. 1987), which reduces to a face-on value of only $\sim 10^2 M_\odot \mathrm{pc}^{-2}$. In this context, the term 'starburst' is still to be defined more clealy by its physics.

3.4. Comparison with the Milky Way Center

Finally, since the Virgo galaxies discussed in this paper are normal spirals, we may compare the properties of the molecular nuclei with that of the central molecular zone (CMZ) of the Milky Way. The central rotation curve of the Milky Way is similar (e.g., Sofue and Rubin 2001), and, thefore, the critical mass density for disk stability in the Galactic Center is about the same: $\Sigma_\mathrm{c} \sim 4 \times 10^3 M_\odot \mathrm{pc}^{-2}$.

According to Oka et al. (1998), the averaged CO intensity in the CMZ in $2^\circ \times 0^\circ.3 \sim 300$ pc $\times$ 40 pc is 6×10^2 K km s^{-1}, which is the value when the molecular disk is seen edge-on from the Sun. If we assume that the gas is uniformly distributed in a disk of diameter ~ 300 pc, the face-on intensity is estimated to be ~ 100 K km s^{-1}, which corresponds to a surface mass density of $\Sigma \sim 2.3 \times 10^2 M_\odot \mathrm{pc}^{-2}$ (table 1). Since the molecular gas is known to be localized in a molecular ring, the surface density will be higher. If we take the ring radius of 120 pc and its thickness a few tens of parsecs (Sofue 1991), the density would be several times higher than that for a uniform disk $\Sigma \sim 10^3 M_\odot \mathrm{pc}^{-2}$. This is sufficiently low for the ring to be stable.

On the other hand, the local density toward Sgr B molecular complex is much higher. The CO intensity toward Sgr B cloud is observed to be $\sim 10^3$ K km s^{-1} (Oka et al. 1998). If the line-of-sight extent of the cloud is about the same as its apparent extent, the face-on SMD of molecular gas is estimated to be $\Sigma \sim 2 \times 10^3 M_\odot$ pc^{-2}. The Toomre's Q value for the complex is about two, close to unity, and, therefore, the Sgr B complex is merginally stable, or could be partially unstable against the gravitational contraction. This may be the reason why Sgr B complex contains the star forming region Sgr B2 as the result of cloud fragmentation.

There arises, however, a question why Sgr B molecular complex itself could form from the satable ring. One possibility is that Sgr B complex is one of the bar ends on the 120 pc ring, with another end at the Sgr C molecualr cloud. In fact, Sgr B is located on the 120-pc molecular ring, which is positionally coincides with one of the ends of symmetrical molecular bars along the central oval potential (Sawada et al. 2004). Hence, the Milky Way center may be in a state of twin peaks, which comprises the two molecular complexes Sgr B and Sgr C at the bar ends located on the 120-pc molecular ring.

This is consistent with the fact that the Milky Way center is not particularly active in star formation at the present. However, it is quite possible that the Galactic Center had contained a much denser gas in the past, comprising a molecular nucleus. Such a molecuar nucleus would have lead to the suggested starburst in the Galactic Center some ten millions ago (Sofue 2000), as inferred from analyses of radio continumm and ROSAT X-ray maps of the whole sky.

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