12CO(J = 1−0) ON-THE-FLY MAPPING SURVEY OF THE VIRGO CLUSTER SPIRALS. I. DATA AND ATLAS

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ABSTRACT
We have performed an On-The-Fly (OTF) mapping survey of 12CO(J = 1−0) emission in 28 Virgo cluster spiral galaxies using the Five College Radio Astronomy Observatory (FCRAO) 14 m telescope. This survey aims to characterize the CO distribution, kinematics, and luminosity of a large sample of galaxies covering the full extents of stellar disks, rather than sampling only the inner disks or the major axis as was done by many previous single dish and interferometric CO surveys. CO emission is detected in 20 galaxies among the 28 Virgo spirals observed. An atlas consisting of global measures, radial measures, and maps is presented for each detected galaxy. A note summarizing the CO data is also presented along with relevant information from the literature. The CO properties derived from our OTF observations are presented and compared with the results from the FCRAO Extragalactic CO Survey by Young et al. which utilized position-switching observations along the major axis and a model fitting method. We find that our OTF-derived CO properties agree well with the Young et al. results in many cases, but the Young et al. measurements are larger by a factor of 1.4−2.4 for seven (out of 18) cases. We will explore further the possible causes for the discrepancy in the analysis paper currently under preparation.

Key words: atlases – galaxies: clusters: individual (Virgo) – galaxies: ISM – radio lines: galaxies

Online-only material: color figures

1. INTRODUCTION
The high galaxy density and proximity make the Virgo cluster a particularly interesting laboratory for galaxy evolution study. Its dynamical evolution is still in progress, and evidence for significant environmental effects is ubiquitous (e.g., Chung et al. 2007). The nearness of the Virgo cluster makes it possible to observe its member galaxies with excellent spatial resolution (1″ ∼ 90 pc). It is the first cluster for which significant H i imaging was done (van Gorkom et al. 1984), and various new H i surveys such as ALFALFA (Giovanelli et al. 2007) and VIVA (Chung 2007) have recently been conducted. The Virgo cluster has also been the subject of many recent multi-wavelength surveys, such as in radio continuum by NRAO VLA Sky Survey (NVSS; Condon et al. 1998), in Hα (Koopmann & Kenney 2004; Chemin et al. 2006), in UV by FAUST (Brosch et al. 1997) and Galaxy Evolution Explorer (GALEX; e.g., Dale et al. 2007), and in IR by Spitzer (Kenney et al. 2008). High-quality optical images are also available from the Hubble Space Telescope (HST)/ACS Virgo Cluster Survey (Cote et al. 2004) and Sloan Digital Sky Survey (SDSS).

Here, we present the results from a new imaging survey of J = 1 − 0 12CO emission in a large sample of Virgo galaxies in order to address the distribution and characteristics of dense molecular gas in these galaxies. It is well established that molecular clouds are the sites of ongoing star formation (Larson 2003 and references therein), and carbon monoxide (CO) is the most commonly used tracer of molecular hydrogen (H₂), which is the most abundant but invisible component of cold and dense clouds (e.g., Solomon & Barrett 1991). The global H₂ content and its distribution in galaxies and a comparison with other gas and stellar components as a function of morphological type, luminosity, and environment are some of the key insights one can derive from CO observations (see Young & Scoville 1991 and references therein).

Existing CO surveys of Virgo cluster galaxies suffer from limited spatial coverage and small sample sizes. The Five College Radio Astronomy Observatory (FCRAO) extragalactic survey (Young et al. 1995) is the first CO survey covering a wide range of distance, diameter, morphological type, and blue luminosity of some 300 galaxies conducted using the FCRAO 14 m telescope, including CO measurements (detections and upper limits) of 65 Virgo galaxies. Because of the large observing time required, these observations were conducted in the position-switching mode, primarily along the optical major axis of the disks, and the global CO line luminosity was derived assuming a model distribution. More recently, high angular resolution CO images have been obtained using interferometric measurements by Sakamoto et al. (1999) and Sofue et al. (2003). These measurements reveal a detailed molecular gas distribution at 100 pc scales, but they are limited only to the central region of galaxies. The BIMA Survey Of Nearby Galaxies (SONG; Helfer et al. 2003) has also carried out an imaging survey of CO emission in several Virgo spiral galaxies, incorporating the short spacing data from the NRAO 12 m telescope. The total number of Virgo galaxies imaged by the BIMA SONG is small (six), however.

These earlier CO observations have revealed important insights on the molecular interstellar medium (ISM) in these galaxies. For example, CO emission is often centrally concentrated, in contrast to the centrally deficient H i distributions commonly found in these galaxies. The molecular gas distribution also shows little evidence for any influence of the gas stripping mechanisms (e.g., Kenney & Young 1989). No central CO peak (Helfer et al. 2003) or nuclear molecular rings (e.g., Iono et al. 2005) are seen in other cases. The influence of cluster...
environment on the molecular content is still poorly understood (e.g., Boselli & Gavazzi 2006).

A distinguishing characteristic of our new CO survey is the complete imaging of $^{12}$CO ($J = 1-0$) emission of a large sample (28 galaxies) of Virgo spirals using the On-The-Fly (OTF) mapping mode of the FCRAO 14 m telescope. Our map size of $10' \times 10'$ is larger than the optical diameter $D_{25}$ and it covers the entire stellar disk of each galaxy. The 45” angular resolution of the new CO images is well matched to the existing VLA H$\alpha$ data and is well suited for comparison with other high-resolution multi-wavelength data. The specific questions we aim to address are as follows.

1. To what extent is the CO distribution governed by the disk dynamics?
2. Is there a clear phase transition between H$\alpha$ and H$_2$ as a function of the interstellar radiation field?
3. Are there any systematic differences in the CO properties of spiral galaxies in different environments?

We present in this paper the data and the CO atlas from our OTF mapping survey. In Section 2, we describe the sample selection. Observations and data reduction process are described in Section 3. The CO atlas and CO properties are presented in Section 4, and our results are compared with those of Young et al. (1995). Molecular gas distribution in individual galaxies is discussed in Section 5, and the summary and conclusion are given in Section 6. The analysis and interpretation of the data addressing the above questions will be presented in our subsequent papers.

2. THE SAMPLE

We initially selected the 42 Virgo spiral galaxies in the magnitude-limited sample studied by Kenney & Young (1988). The primary goal of our project is investigating the spatially resolved distribution of molecular gas and their relation to other tracers of activities among the Virgo spirals, and a large angular size is an important consideration. We also considered the total CO flux to increase the detection rate. Given the observing time limitations, a subset of 28 galaxies was observed in the order of CO strength ($S_{CO} \geq 200$ Jy km s$^{-1}$) and included in this study. The observed galaxies have an optical diameter of 3–10 arcmin and span a wide range of properties (Sa to Sc), surface brightness ($9 \leq B_{T}^0 < 12$), and dust mass ($10^6 M_\odot \leq M_{dust} \leq 10^7 M_\odot$). The basic properties of the observed galaxies are summarized in Table 1 and are illustrated in Figure 1.5

3. OBSERVATIONS AND DATA REDUCTION

3.1. Observations

We carried out OTF mapping observations of CO emission in 28 Virgo galaxies over several observing sessions between 2002 January and 2003 February using the SEcond QUabbin Optical Imaging Array (SEQUOIA) focal plane array receiver on the FCRAO 14 m telescope. The SEQUOIA consists of 16 horns, each with 45” beam size, configured in a 4 × 4 array. The backend system used is the Quabbin Extragalactic Filterbanks (QEFs), which consists of 16 independent spectrometers each with 64 channels at 5 MHz resolution, resulting in a total bandwidth of 320 MHz ($AV \sim 830$ km s$^{-1}$). These spectra are calibrated using the standard chopper-wheel method which corrects for atmospheric and ambient temperature losses to yield the corrected antenna temperature $T_A^*$.  

In the OTF mapping mode, the telescope moves fast and smoothly across the target field taking the data continuously, and each map pixel is sampled independently by all 16 independent detector pixels. Therefore, the use of the OTF observing mode offers a significantly improved calibration, relative pointing accuracy and registration, and a much higher dynamic range over the traditional pixel-by-pixel mapping mode. Our OTF observations have fully covered the entire stellar disk of each galaxy multiple times. Typically, a $10' \times 10'$ size box centered on each galaxy is mapped with a scan speed of 45” per second, and the data are stored in every 0.25 s. A reference spectrum is obtained after every or every other row of scan at a location 30’ away in the azimuth direction. A 6’ × 4’ region is mapped for NGC 4536 because of a telescope problem during the observations. NGC 4567 and NGC 4568 is an interacting pair observed simultaneously using a single scanning box, and one data cube contains both galaxies.

The pointing and focus of the telescope are measured at 2–4 hr intervals by observing the 86 GHz SiO maser in R-Leo. The measured rms pointing error is $\sim 3''$ in both azimuth and elevation, or $\sim 5''$ total.

3.2. Data Reduction

The data reduction is carried out in two steps, initially using the revised-OTFTOOL (Chung et al. 2006) and later the Groningen Image Processing SYstem6 (GIPSY; van der Hulst et al., 1992) package. The revised-OTFTOOL reads in the raw OTF data and produces a map after the initial editing and calibration. The resulting data cubes are written out in FITS format and are imported to the GIPSY environment for further data reduction and analysis.

The revised-OTFTOOL is a newly developed program based on the OTFTOOL, which is the FCRAO facility pipeline software for the SEQUOIA OTF data. The OTFTOOL was designed primarily for the reduction of narrow Galactic emission line data taken with the digital backend, and the default data filter is not well suited for the baseline removal in the presence of weak, broad emission lines seen in extragalactic $^{12}$CO data. The revised-OTFTOOL includes several new functions that are specifically designed to produce noise-limited output images, with improved data filtering and baseline fitting. An improved filtering algorithm in the revised-OTFTOOL identifies and removes bad spectra using the rms level, antenna trajectory, elevation, and system temperature/gain ($T_{sys}$), and data containing spikes are identified and excluded. A second major improvement is the implementation of a new self-referencing method. Rather than using the conventional “OFF” spectrum, our self-referencing method constructs the best OFF spectrum from the ON spectra and system baseline removal in the spatial and spectral domain (see Chung et al. 2005a, 2005b for more details). This self-referencing method produces an OFF spectrum temporally much closer to the ON spectra, significantly reducing the influence of any residual gain changes and thus a significantly improved baseline behavior. Finally, the data are normally weighted and mapped onto a regular 15” grid.

The GIPSY package is used to produce the final data cubes from the individual scan maps. Occasional bad filter bank channels are removed and replaced with new data generated

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5 The E-SO galaxy NGC 4649 is included in our sample because it is a companion of a late-type spiral NGC 4647.

6 http://astro.rug.nl/~gipsy
by interpolating two or more adjacent channels. Interpolation should produce a reasonable result since the channel separation ($\Delta V \sim 13 \text{ km s}^{-1}$) is small compared with the intrinsic CO line width in these galaxies. Data cubes including only the CO emission, used for further spectral analysis, are created in two steps. First, a data mask for the CO emission region is created through an iterative algorithm that identifies the signal regions with criteria of 1.5 rms and minimizes the noise in the line-free regions through a removal of a low-order ($n \ll 2$) polynomial baseline in the frequency domain. Then the final “signal-only” data cube is obtained from the noise-minimized data cube by excluding the noise part and retaining the emission regions. For six galaxies which have large inclination ($\gtrsim 80$ degree) or weak emission (signal-to-noise ratio ($S/N \lesssim 2.5$), position–velocity diagram (PVD) is used to obtain physical quantities.

### 4. RESULTS

Among the 28 galaxies observed, 20 galaxies including a galaxy pair of NGC 4567 and NGC 4568 are detected in CO emission. The CO detected galaxies are classified into two groups: (1) 14 galaxies with strong emission features in the channel map with $S/N \gtrsim 2.5$ (Group I); and (2) six galaxies with large inclination $\gtrsim 80$ degree or weak CO emission with $S/N \lesssim 2.5$ (Group II). We have produced a CO atlas for these galaxies and derived their CO properties. NGC 4567 and NGC 4568 are an interacting pair, poorly resolved by our spatial and velocity resolutions. Therefore, their measured and derived properties are reported as a single object. The results of NGC 4556 are derived from $6' \times 4'$ size data cube.

#### 4.1. CO Atlas: Map Descriptions

Figures 2–17 are the CO atlas and selected channel maps of Group I and Group II galaxies obtained from our OTF mapping observations. The atlas figure for each Group I galaxy consists of six maps: a CO intensity map (top left), a velocity field map (top right), an optical image with CO contours (middle left), a PVD derived along the major axis of the stellar disk (middle right), a global CO line profile (bottom left), and a radial CO profile (bottom right). Selected channel maps are also shown for Group I galaxies. For Group II galaxies, CO emission is too faint to yield an intensity map and velocity-field map. Therefore, only an optical $B$-band image from NASA/IPAC Extragalactic Database (NED\(^7\); top left), a PVD derived by integrating along the minor axis (top right), a global CO line profile (bottom left), and a radial CO profile (bottom right) are shown.

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\(^7\) http://nedwww.ipac.caltech.edu
Figure 1. Sample properties as a function of (a) morphological type (LEDA), (b) the major axis diameter at 25th mag arcsec$^{-2}$ in the B band (LEDA), (c) corrected total B-band magnitude (LEDA), and (d) angular distance from M87. The white region represents the 28 Virgo galaxies observed, and the shaded region corresponds to the 20 galaxies that are detected in CO.

Figure 2. Group I-1. CO atlas and channel maps of NGC 4254. CO intensity map (top left), velocity field map (top right), CO contours overlapped on the optical B-band image (middle left), PVD which is the central slice along the major axis of data cube (middle right), global CO line profile (bottom left), and radial CO distribution (bottom right). The line of radial profile is the average of the east- and west-side values for each radial position. The channel maps are shown over the velocity range of emission. The numbers on top right of the first and second channels represent the velocities in km s$^{-1}$, and their difference is the channel velocity separation.

(A color version of this figure is available in the online journal.)
Figure 3. Group I-2. Same as Figure 2 for NGC 4302. In the optical image, the companion galaxy NGC 4298 is visible in the west. (A color version of this figure is available in the online journal.)

Figure 4. Group I-3. Same as Figure 2 for NGC 4303. (A color version of this figure is available in the online journal.)
Each map shown (including the channel maps) has a dimension of \( 6' \times 6' \) (\( 4' \times 4' \) for NGC 4536) since no emission was detected outside of this region for all galaxies. The velocity range shown for the global CO profile and channel map is about 500 km s\(^{-1}\), except for NGC 4501 which has a CO line width of about 520 km s\(^{-1}\). The contour levels shown are listed in Table 2.

**CO intensity map.** A CO intensity map is produced by summing all emission features in the channel maps. The contour levels shown are listed in K km s\(^{-1}\), and the CO line intensity is in the \( T_A^* \) scale.

**Velocity field map.** A mean velocity field map is derived through single Gaussian fit to the observed line profiles.

**Position–Velocity diagram.** A PVD is extracted from a row of pixels along the major axis, i.e., a central slice of 15 arcsec width is shown in ATLAS, for Group I galaxies. For Group II galaxies, whose inclination is too high or whose CO emission is too weak in the individual channel maps, an integrated PVD is produced by summing the data along the minor axis. The integration is done over some minor axis length for each galaxy (1 or 2 beamwidth for highly inclined galaxies and up to 7 beamwidth for weak CO and face-on galaxies).

**Global CO line profile.** For Group I galaxies, a global CO line profile is extracted from the data cube. For Group II galaxies, CO flux density is integrated manually along the minor profile is extracted from the data cube. For Group II galaxies, whose inclination is too high or whose CO emission is too weak in the individual channel maps, an integrated PVD is produced by summing the data along the minor axis. The integration is done over some minor axis length for each galaxy (1 or 2 beamwidth for highly inclined galaxies and up to 7 beamwidth for weak CO and face-on galaxies).

**CO properties for the 20 CO detected Virgo spiral galaxies are summarized in Table 3. The column entries are:**

- (1) NGC number;
- (2) rms noise measured from emission-free regions;
- (3) line width measured at 20% level;
- (4) line width at 50% level;
- (5) systemic velocity derived from the CO velocity profile;
- (6) total CO line flux;
- (7) molecular hydrogen mass;
- (8) effective CO diameter;
- (9) isophotal CO diameter.

**Total CO flux and \( \text{H}_2 \) mass.** To convert the CO intensity in \( T_A^* \) into the flux density unit, a calibration factor of 42 Jy K\(^{-1}\) obtained using the FCRAO 14 m telescope (Kenney & Young 1988) is applied. We derive \( \text{H}_2 \) masses from total CO flux measured assuming a linear conversion relation (Kenney & Young 1989),

\[
M_{\text{H}_2} = 3.9 \times 10^{-17} \chi d^2 S_{\text{CO}} (M_\odot),
\]

where \( \chi \) is the conversion factor and \( d \) is distance to the source in megaparsecs (Mpc). We adopt \( \chi = 3 \times 10^{20} \text{cm}^{-2} \text{K}[\text{m} \text{s}^{-1}]^{-1} \) (Young & Scoville 1991). The distance to the Virgo cluster is somewhat uncertain because of the large depth effect (Yasuda et al. 1997) and is generally thought to be between 15 and 20 Mpc (e.g., Young et al. 1995; Sakamoto et al. 1999; Sofue et al. 2003; Sandage & Tammann 2006; Mei et al. 2007). We adopt a distance of 20 Mpc for an easier comparison with the FCRAO Extragalactic CO Survey (see Section 4.3).

**CO line width.** CO line width is measured at 20% and 50% level of the line peak, on each side of the line, following the definition of Rhee (1996). The line profile is divided into two equal velocity bins, and the peak fluxes \( T_{\text{low}} \) and \( T_{\text{high}} \) are determined separately on each half of the line profile. The 20% and 50% velocities \( V_{20\%} \) and \( V_{50\%} \) represent the velocities at which the line profile reaches the 20% and 50% of the peak value on the respective high- and low-velocity side, approaching from the line edge to the center of the line profile. A linear interpolation procedure is used in this calculation.

The final value of line width of each cutoff level is determined as

\[
W_{\text{obs}}^{20} = V_{\text{high}}^{20\%} - V_{\text{low}}^{20\%},
\]

\[
W_{\text{obs}}^{50} = V_{\text{high}}^{50\%} - V_{\text{low}}^{50\%}.
\]

The uncertainty in the line width is estimated with 1σ uncertainty in each case where σ is the mean rms noise of line-free channels (Rhee & van Albada 1996).

The line width is corrected for instrumental broadening following the method described by Verheijen (1997). The correction for instrumental broadening (in km s\(^{-1}\)) is computed as

\[
W_{20} = W_{\text{obs}}^{20} - 35.8 \left[ \frac{\Delta V}{23.5} \right]^2 - 1, \quad (8)
\]

\[
W_{50} = W_{\text{obs}}^{50} - 23.5 \left[ \frac{\Delta V}{23.5} \right]^2 - 1, \quad (9)
\]

where \( \Delta V \) is the velocity resolution in km s\(^{-1}\).

**CO systemic velocity.** Again, following the procedure described by Verheijen (1997), we compute the systemic velocity of each galaxy as

\[
V_{\text{sys}} = \left( \frac{V_{\text{low}}^{20\%} + V_{\text{high}}^{20\%} + V_{\text{low}}^{50\%} + V_{\text{high}}^{50\%}}{4} \right), \quad (10)
\]

**CO diameters.** To describe CO extents, we derived effective diameters and isophotal diameters. Effective CO diameter, \( D_{\text{eff}}^{\text{CO}} \), is defined as a diameter which encloses 70% of the total emission.
Figure 5. Group I-4. Same as Figure 2 for NGC 4321.
(A color version of this figure is available in the online journal.)

Figure 6. Group I-5. Same as Figure 2 for NGC 4501.
(A color version of this figure is available in the online journal.)
Figure 7. Group I-6. Same as Figure 2 for NGC 4527. (A color version of this figure is available in the online journal.)

Figure 8. Group I-7. Same as Figure 2 for NGC 4535. (A color version of this figure is available in the online journal.)
Figure 9. Group I-8. Same as Figure 2 for NGC 4536.

(A color version of this figure is available in the online journal.)

Figure 10. Group I-9. Same as Figure 2 for NGC 4567 and NGC 4568. NGC 4567 is in the center, and NGC 4568 is in the south. The PVDs and radial CO distributions are obtained according to each galaxy’s center and position angle.

(A color version of this figure is available in the online journal.)
Figure 11. Group I-10. Same as Figure 2 for NGC 4569.
(A color version of this figure is available in the online journal.)

Figure 12. Group I-11. Same as Figure 2 for NGC 4647. In the optical image, the elliptical companion galaxy NGC 4649 is visible in the east.
(A color version of this figure is available in the online journal.)
The CO isophotal diameter, $D_{CO,iso}$, is defined as the diameter where the mean face-on surface density of H$_2$ falls to $1 M_\odot$ pc$^{-2}$ which corresponds to $\int T_R dv = 0.21$ K km s$^{-1}$, or $6.3 \times 10^{19}$ H$_2$ cm$^{-2}$ for a CO–H$_2$ proportionality factor of $\chi = 3 \times 10^{20}$ cm$^{-2}$ (K[T$_R$] km s$^{-1}$)$^{-1}$ (Young & Scoville 1991).

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4.3. Comparison with Other Observations

Previous single dish and interferometric CO measurements exist for many of our target galaxies. A comparison of our results with those of the FCRAO Extragalactic CO Survey (Young et al. 1995) and the BIMA SONG (Helfer et al. 2003) provides an important test of potentially important systematics associated with these two widely utilized extragalactic CO surveys.

4.3.1. Comparison with the FCRAO Extragalactic CO Survey

The FCRAO extragalactic CO survey (Young et al. 1995) data on 300 external galaxies is the most extensive and most widely referenced database for CO emission measurements in 300 external galaxies. A comparison of our results with those of the FCRAO Extragalactic CO Survey (Young et al. 1995) and the BIMA SONG (Helfer et al. 2003) provides an important test of potentially important systematics associated with these two widely utilized extragalactic CO surveys.

A comparison of the FCRAO 14 m OTF and PS measurements is summarized in Table 4. Both the raw PS ($S_{PS,obs}^{CO}$) and the model fit ($S_{PS,fit}^{CO}$) results are listed, using the scale factor (scf) given in the original paper (Young et al. 1995). An isophotal diameter $D_{iso}^{OTF}$ is defined as the diameter where the face-on CO integrated intensity falls to 1 K(T$_R$) km s$^{-1}$, while an effective diameter $D_{eff}^{OTF}$ is defined as the diameter which contains 70% of the total CO flux, following the definition by Young et al. (1995). The fractional ratio between the OTF and PS measurements, $r$, is calculated and presented to show the difference between the two methods of the total CO flux. Comparisons of the OTF and PS measurements are also shown in Figure 18.

Panel (a) in Figure 18 shows that the observed PS line fluxes are systematically smaller than the OTF measurements, but this is expected since “observed PS” data include only partial measurements taken along the major axis. A better agreement is expected for galaxies with a high inclination and a small size. And indeed galaxies with a smaller $D_{25}$ and a larger inclination appears to have a smaller discrepancy between $S_{PS,obs}^{CO}$ and $S_{PS,fit}^{CO}$. The model-fit measurements shown in panel (b) are more consistent with the OTF measurements. The OTF and PS model-fit measurements of nine galaxies are consistent with the total CO flux to within 1$\sigma$. Out of the remaining nine galaxies, seven show larger $S_{PS,fit}^{CO}$ than $S_{OTF}^{CO}$ by a factor of 1.4–2.4. And, the last two galaxies (NGC 4438 and NGC 4548) have larger $S_{OTF}^{CO}$ than $S_{PS,fit}^{CO}$ by a factor of 1.4. Among the nine galaxies for which measured difference is narrowly constrained to the differences in the observing methods and the modeling used by Young et al. NGC 4536 is excluded in this comparison because the small area coverage of our maps may have adversely affected the baseline subtraction process.

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the discrepancies are larger than $1\sigma$, there are four galaxies which disagree by $\geq 2\sigma$ uncertainty, and the four galaxies have larger $S_{\text{PS}}$ than $S_{\text{OTF}}$ by a factor of 1.6–2.4. We predict that peculiar CO distributions such as ring- or bar-like structures (e.g., Young et al. 1995) can affect the model fitting process, and more analysis will be done in another paper (E. J. Chung...
et al. 2010, in preparation). Panels (c) and (d) in Figure 18 show the comparisons of CO diameters derived from the OTF and PS observations. For Group I galaxies detected with high S/N, isophotal diameters derived from the OTF data ($D_{\text{OTF}}^{\text{iso}}$) are larger than those of the PS data ($D_{\text{PS,fit}}^{\text{iso}}$). In contrast, the effective diameters of OTF ($D_{\text{OTF}}^{\text{eff}}$) are smaller than $D_{\text{PS,fit}}^{\text{eff}}$. An explanation for these apparently puzzling trends is that CO emission is spread over a larger extent but has a more concentrated central component in the OTF maps when compared with the results of Young et al. (1995). The effective diameters $D_{\text{OTF}}^{\text{eff}}$ are smaller than 3 arcmin in every case, and the isophotal diameters are located between 1/2 and 1 of the optical diameter $D_{25}$ in most cases. $D_{\text{OTF}}^{\text{iso}}$ for Group II galaxies are systematically smaller than $D_{\text{PS,fit}}^{\text{iso}}$, and this may be the result of low S/N of the OTF data.

4.3.2. Comparison with the BIMA SONG Survey

Three galaxies imaged in the OTF mode (NGC 4303, NGC 4321, and NGC 4569) were also observed by the BIMA SONG project (Helfer et al. 2003). The total BIMA SONG CO fluxes reported for NGC 4303, NGC 4321, and NGC 4569 are 2427 ± 145, 2972 ± 319, and 1096 ± 137 Jy km s$^{-1}$, respectively. These integrated CO line fluxes are systematically
NGC 4302. This Sc galaxy is a dusty edge-on spiral located 3′1 northwest of M87. Its CO distribution in our CO intensity map consists of two molecular peaks with a central depression. Young et al. (1995) modeled the CO distribution as being offset by 0′45 from its center. Our new data suggest that this earlier study might have detected only one of the two peaks.

NGC 4301. This Sc spiral is located 8′2 south of M87. Cayatte et al. (1990) reported a symmetric H\textsc{i} distribution with a central depression. Our atlas shows that CO emission is distributed along the spiral arms, and a bar-like structure is displaced in position angle by about 20 degrees. Helfer et al. (2003) reached the same conclusion using the BIMA SONG survey data. The CO emission is concentrated in the central region, unlike the H\textsc{i} and CO velocity fields are in good agreement. A recent burst of star formation caused by tidal interactions with two nearby companions has been suggested by Cayatte et al. (1990).

NGC 3251. This Sc galaxy is located 3′9 north of M87. Its H\textsc{i} emission is distributed along the spiral arms, and the oval distortion in the inner part due to the presence of a bar is shown from the kinematic pattern (Cayatte et al. 1990). Our CO image shows a well confined CO distribution on the stellar disk, plus an asymmetric extension to the southern spiral arm. It also has an elongated bar-like structure along the major axis. The CO velocity field shows an oval distortion in the inner part, similar to the H\textsc{i} (Cayatte et al. 1990). The BIMA SONG survey detected CO at the center and along the spiral arms (Helfer et al. 2003), in a good agreement with our results. Sakamoto et al. (1999) reported a prominent pair of nuclear CO arms and a sharp condensation of CO at the nucleus. Chemin et al. (2006) found three different pattern speeds, which is a sign of streaming motion.

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NGC 4501. This Sbc spiral is located 2:1 north of M87. Cayatte et al. (1990) reported that this galaxy points its steep H i edge toward M87, similar to NGC 4254, and suggested these two galaxies as examples of enhanced star formation caused by compression of the ISM. Our CO intensity map shows a well centered distribution. Sakamoto et al. (1999) reported a concentrated CO morphology, and Sofue et al. (2003) found that the northeastern arm is much brighter in CO than the southwestern arm. The CO velocity width of NGC 4501 is one of the largest among the galaxies observed. The Hα velocity field appears regular, but the PVD shows a complex kinematics (Chemin et al. 2006).

NGC 4527. This Sb galaxy is located 9:8 south of M87. Kenney & Young (1988) reported that it has a uniform disk component. Our OTF map is consistent with the Young et al. data, but the OTF map shows that there is a central CO concentration along with a bar along the major axis and an asymmetric extension to the southwest.

NGC 4535. This Sbc spiral is located 4:3 south of M87. This galaxy shows an undisturbed H i distribution with a central hole (Cayatte et al. 1990). Helfer et al. (2003) reported that CO is distributed at the center and along the spiral arms. Sofue et al. (2003) classified this galaxy as a typical single-peak type with offset bars. Our OTF data is noisy, and the signal is very weak. The CO intensity map shows a bar-like elongated structure in the central region, and the PVD shows evidence for highly disturbed gas kinematics. Chemin et al. (2006) reported a perturbed velocity field and streaming motions along the arms.

NGC 4536. This Sc galaxy is located 10:2 south of M87. Our map covers only a 6′ × 4′ region, but the CO emission appears to be fully covered when compared with the CO map of Kenney & Young (1988). CO emission is strongly concentrated on the galactic center, and this agrees well with the results by Sofue et al. (2003).

NGC 4567 and 4568. These two Sc galaxies are located 1:8 away from M87, and they are not well separated spatially or kinematically. Cayatte et al. (1990) suggested that the H i emission displaced toward the south of NGC 4567 could be a sign of a tidal interaction between the two galaxies. Koopmann & Kenney (2004) also suggested ram pressure effects and a tidal interaction between the two. However, Hα velocity field does not show any clear signs of velocity disturbances (Chemin et al. 2006). Higher angular resolution H i and CO observations by Iono et al. (2005) also show that the inner gas disks show little signs of tidal disturbance, with a symmetric bar-like or spiral-like features. Unlike many other observed Virgo galaxies, they both show CO emission extending out to the outer optical radii in our OTF map, including where the two disks overlap.

NGC 4569. This Sab spiral is an H i-anemic galaxy (van den Bergh 1976) located 1:7 northeast of M87. Cayatte et al. (1990) reported that its H i disk is severely stripped. Interferometric CO imaging found a symmetric CO distribution with two peaks and a central depression (Helfer et al. 2003; Sofue et al. 2003). Higher resolution CO imaging by Nakanishi et al. (2005) found a highly concentrated CO distribution in the circumnuclear region with two off-center peaks. Our CO atlas shows a centrally
continuum, and the Hα CO peak is well centered on the stellar disk. The lopsided CO maps also show a clear asymmetry and lopsidedness, but the CO distribution in the inner region and suggested that even the CO appearance toward NGC 4649 (Cayatte et al. 1990). However, CO appears to point away from its optical major axis. Its Hα image shows a sharp cutoff on the northwest side and an extension is both to the northwest and to the southwest, in the direction of M87. The Hα velocity field is strongly perturbed (Chemin et al. 2006).

NGC 4689. This Sc galaxy is located 4.3 northeast of M87. It has a large, extended H I disk (Cayatte et al. 1990). High angular resolution CO imaging by Sofue et al. (2003) found a lopsided, amorphous CO morphology and without a central peak. Our CO map shows a CO peak offset from the optical center and extended to the south. Chemin et al. (2006) reported that Hα velocity field is slightly perturbed due to streaming associated with pseudo-spiral arms.

5.1.2. Group II Galaxies

NGC 4298. This Sc galaxy is located 3.2 northwest of M87 and has a companion elliptical galaxy NGC 4302. NGC 4298 shows a slightly extended H I distribution toward NGC 4649 (Cayatte et al. 1990). However, CO appears to point away from its elliptical companion NGC 4649 in our intensity map. The CO PVD also appears disturbed. The companion galaxy NGC 4649 is undetected in CO.

NGC 4647. This Sc galaxy is located 3.2 east of M87 and has a companion elliptical galaxy NGC 4649. NGC 4647 shows a slightly extended H I distribution toward NGC 4649 (Cayatte et al. 1990). However, CO appears to point away from its elliptical companion NGC 4649 in our intensity map. The CO PVD also appears disturbed. The companion galaxy NGC 4649 is undetected in CO.

NGC 4654. This Sbc galaxy is located 3.3 northeast of M87. The H I image shows a sharp cutoff on the northwest side and an eastward extension, and enhanced star formation activity is also seen in the northwest (Cayatte et al. 1990). Kenney & Kenney (1988) found an asymmetric CO distribution—the position 45° northwest of the nucleus shows a stronger line than the central 45°, and this region also displays a peak in the H I, radio continuum, and the Hα. Sofue et al. (2003) found a lopsided CO distribution in the inner region and suggested that even the region nucleus suffers from the ram pressure effects. Our OTF CO maps also show a clear asymmetry and lopsidedness, but the CO peak is well centered on the stellar disk. The lopsided CO extension is both to the northwest and to the southwest, in the direction of M87. The Hα velocity field is strongly perturbed (Chemin et al. 2006).

NGC 4627. This Sc galaxy is located 4.3 northeast of M87. It has a large, extended H I disk. High angular resolution CO imaging by Sofue et al. (2003) found a lopsided, amorphous CO morphology and without a central peak. Our CO map shows a CO peak offset from the optical center and extended to the south. Chemin et al. (2006) reported that Hα velocity field is slightly perturbed due to streaming associated with pseudo-spiral arms.

5.1.2. Group II Galaxies

NGC 4298. This Sc galaxy is located 3.2 northwest of M87 and has a companion NGC 4302 only 2.3 arcmin away. Stellar asymmetry due to a recent tidal interaction is seen in optical images, and a truncated gas disk due to ram pressure is also suggested (Koopmann & Kenney 2004). Chemin et al. (2006) suggested that its mildly perturbed velocity field may indicate a streaming motion or a locally warped arm. Our PVD shows stronger emission on the east (receding) side than on the west (approaching) side, and CO emission is probably extended toward southeast side, in the direction of its companion galaxy NGC 4302. This feature is in good agreement with the Hα kinematics discussed above.
NGC 4402. This edge-on Sc galaxy is located 1°4 northwest of M87. Although the high velocity part of the H\textsc{i} emission is missed by Cayatte et al. (1990), it is obvious that the H\textsc{i} disk of this galaxy is significantly smaller in extent than that of the optical disk. Our CO PVD shows that CO emission is asymmetric to one side, and Young et al. (1995) also suggested the distribution model to be offset by 0°20 from the center. A 10'' radius nuclear disk and a more extended molecular disk with a 30'' diameter are found by higher angular resolution observations (Sofue et al. 2003).

NGC 4419. This Sa galaxy is located 2°8 north of M87. Kenney & Young (1988) proposed that NGC 4419 is on a radial orbit which passes very close to the cluster core and strongly interacts with the intracluster medium, resulting in a large CO/H\textsc{i} flux ratio and a significant CO asymmetry. The CO distribution model of Young et al. (1995) shows an offset 0°25 from center, and Sofue et al. (2003) reported that the outer molecular disk is lopsided toward the northwest. Our CO PVD shows a compact distribution and a rapidly rising rotation speed in the central region.

NGC 4438. This Sb galaxy is located 1°0 northwest of M87. Cayatte et al. (1990) reported a highly asymmetric H\textsc{i} distribution with an extension pointing away from M87, and a much smaller H\textsc{i} disk than the optical disk. Its ionized gas has an off-plane filamentary morphology to the east and south of the disk (Chemin et al. 2006; Kenney et al. 1995; Kenney & Yale 2002). Our CO PVD shows that its molecular center is offset from the optical center by ∼0.5 arcmin to the east. It also shows a highly disturbed structure.

NGC 4548. This SBb galaxy is located 2°4 northeast of M87. This galaxy is a nearly face-on barred (SBb) spiral which is severely H\textsc{i} deficient (van den Bergh 1976; Giovanelli & Haynes 1983). Cayatte et al. (1990) reported a ring structure in the H\textsc{i} distribution. The BIMA SONG survey detected CO only at the center (Helfer et al. 2003), and Sofue et al. (2003) also reported a very weak and highly concentrated CO distribution. Our CO data are weak and too noisy to determine the molecular distribution well. However, its global CO line profile shows moderately symmetric double horns and CO appears to have comparatively large extent from the integrated PVD and radial profile.

NGC 4579. This Sab galaxy is located 1°8 east of M87 and is another H\textsc{i}-anemic spiral (van den Bergh 1976). Its H\textsc{i} distribution shows a ring-like structure, and is the most severely stripped galaxy with signs of unusual nuclear activity, possibly fueled by gas inflow (Cayatte et al. 1990). The BIMA SONG survey detected CO only at the center (Helfer et al. 2003), and Sofue et al. (2003) reported that elongated CO distribution is displaced from the optical bar axis by about 30 degrees. Its H\textsc{α} velocity field shows evidence for perturbed, streaming motions (Chemin et al. 2006). Our CO PVD shows a severely disturbed morphology and kinematics.

5.2. Summary of CO Distribution

Here, we summarize the CO distribution of the Virgo spiral galaxies shown by our survey.

1. CO is confined to the galactic center and disk in most galaxies. However, slight asymmetric distribution and significant
structures as well as kinematic disturbances are frequently shown. This is consistent with previous results of CO studies (e.g., Young et al. 1995; Helfer et al. 2003).

2. Among the 14 galaxies which have CO intensity maps, 11 galaxies have single CO peak center (NGC 4254, NGC 4303, NGC 4321, NGC 4501, NGC 4527, NGC 4535, NGC 4536, NGC 4567, NGC 4568, NGC 4569, and NGC 4654). NGC 4302 has twin peaks with a central depression, and NGC 4647 and NGC 4689 have no notable CO peak at the center.

3. Five galaxies appear to have bar-like elongated structure (NGC 4303, NGC 4321, NGC 4501, NGC 4536, and NGC 4569). Extended CO distributions to one side are also seen in six galaxies (NGC 4254, NGC 4298, NGC 4527, NGC 4564, NGC 4689, and NGC 4402).

4. CO emission in NGC 4298 shows an asymmetric extension toward the southeast, which is the direction of its companion galaxy NGC 4302. NGC 4647 shows a CO distribution pointing away from its elliptical companion NGC 4649.

Figure 19 shows the total CO extent and morphology of each of the 14 Group I galaxies at their proper position in the Virgo cluster. There are several noteworthy trends.

1. It appears that CO molecules are not strongly affected by the cluster environments such as distance from the cluster center of M87.

2. Galaxies located in the western side of Virgo Cluster are known to have a larger H I disk than the galaxies in the eastern side (Cayatte et al. 1990), and we find the same trend in the CO disk size as well.

3. NGC 4298 and NGC 4647 have companion galaxies, but CO emission is extended toward and on the opposite to its companion, respectively. Figure 19 suggests that both of their extensions point toward the cluster center near M87. NGC 4654 also shows a CO extension toward M87.

6. SUMMARY AND CONCLUDING REMARKS

We have carried out a \(^{12}\)CO\((J = 1-0)\) OTF mapping survey of 28 Virgo cluster spiral galaxies. Although the importance of molecular contents in galaxy evolution is widely recognized, systematic CO imaging surveys of a large galaxy sample covering the full extent of the stellar disks are still rare. Taking advantages of the OTF mapping mode of the FCRAO 14 m telescope, we have imaged a large area of each galaxy covering the entire stellar disks in a relatively short period of time compared with the more traditional position-switched grid-map mode.

We detected and mapped CO emission in 20 of the galaxies with uniform sensitivity. Here we present their global CO properties. The CO emission is generally well centered on the stellar disk. However, some Virgo spirals show extended CO distribution to one side or bar-like CO distribution. The comparison of our CO data with those of the FCRAO extragalactic CO survey (Young et al. 1995) suggests that the major axis scan and
global modeling used by Young et al. was largely successful in estimating the total CO luminosity. Young et al. have larger CO luminosities than our results for seven (four) out of 18 galaxies by 1σ (2σ) uncertainty. Further analysis of these data will be presented in our future papers. Extensive multi-wavelength data are now available for joint analysis with our new CO data, including the H I (Chung et al. 2007), radio (Yun et al. 2001), IR (Spitzer and Akari), optical (HST and SDSS), Ha (Koopmann & Kenney 2004), and UV (GALEX). We will examine radial dependence of the star formation rate and star formation efficiency. Their dependence on the morphological type, luminosity, and environments will also be studied using the global CO properties. To study environmental effects in different cluster evolutionary stages, we will use our Virgo data with the OTF mapping data of Ursa Major cluster spiral galaxies (A. Chung et al. 2010, in preparation) and single dish spectra of the Pisces filament spiral galaxies (M. Y. Lee et al. 2010, in preparation) obtained using the Kitt Peak 12 m telescope. We will also explore the utility of the CO Tully–Fisher relation.

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