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The Virgo High-Resolution CO-Line Survey

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Abstract. We present the results of the Virgo high-resolution CO survey (VCOS) obtained with the Nobeyama Millimeter-wave Array at high-angular and spectral-resolutions in the ^{12}CO ($J = 1 - 0$) line emission for 15 Virgo CO-rich spirals. The central CO distributions can be classified into the "central/single-peak type", which is a majority, and "twin-peaks". We derived exact rotation curves by applying a new iteration method to position-velocity diagrams, which show generally a steep central rise, indicating central massive cores.

1. Introduction

High-resolution CO-line observations play an essential role in studying the kinematics and ISM physics in the central regions of spiral galaxies. The Virgo high-resolution CO survey with the NMA has been performed in order to obtain a high angular- and spectral-resolution database for a large number of CO-bright Virgo Cluster spirals in the ^{12}CO ($J = 1 - 0$) line (Sofue et al. 2003a,b). The major motivation was to investigate the detailed rotation curves from analyses of position-velocity diagrams across the nuclei, which would be effective in detecting central compact massive objects. The data are also useful for investigation of the kinematics and ISM physics of the central molecular disks, and their environmental effect in the cluster circumstance. The advantage of observing the Virgo Cluster galaxies is their identical distance, which has been accurately taken as 16.1 Mpc by Cepheid calibrations (Ferrarese et al. 1996).

2. Observations and Results

The target galaxies in the survey have been selected from the list of Kenney & Young (1988) by the following criteria. The sources were chosen in the order of CO peak antenna temperatures at the optical centers. Inclination angles were limited to be $25° \leq i \leq 75°$ in order to investigate central gas dynamics.

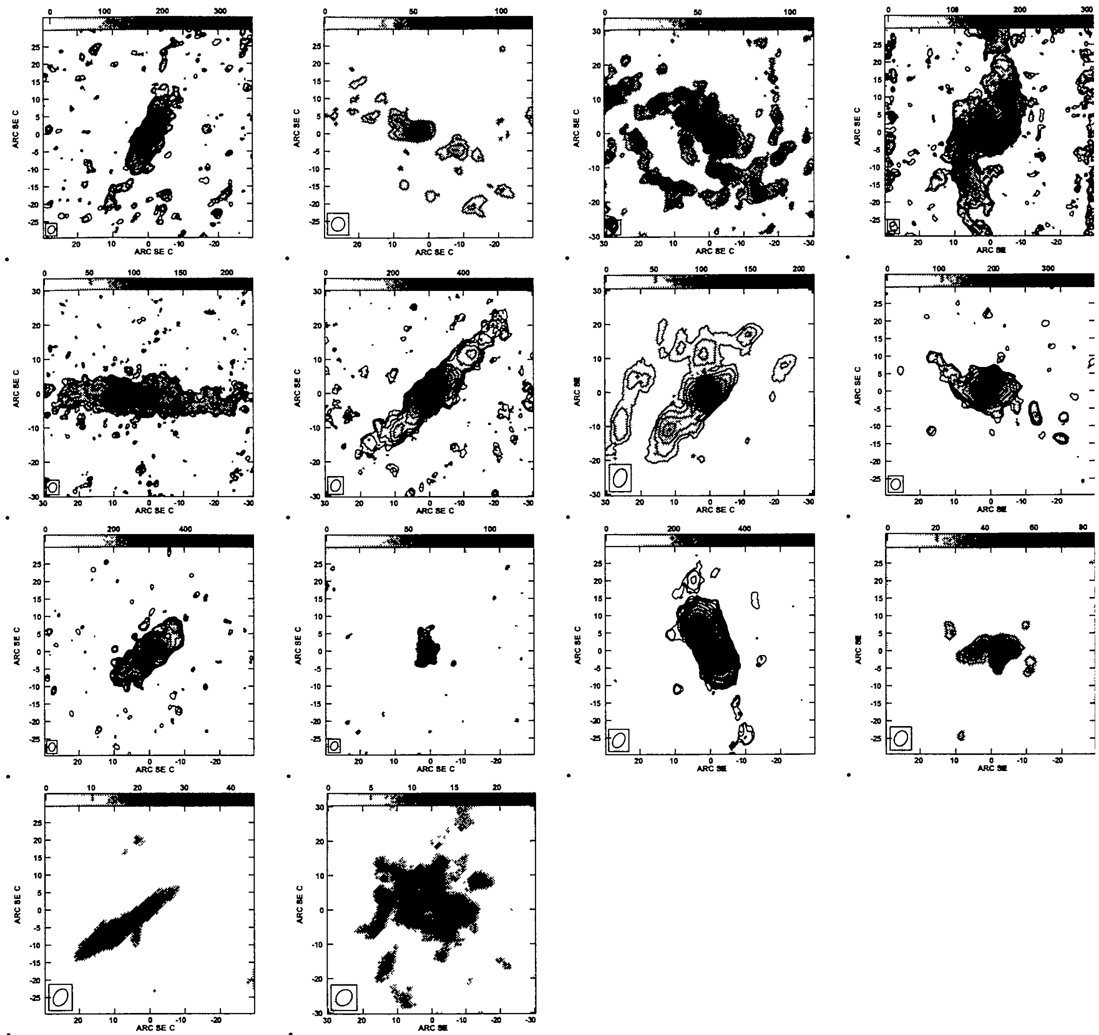

Figure 1. CO atlas of the observed Virgo galaxies. Integrated ^{12}CO ($J = 1 - 0$)-intensity maps. The image sizes are 1.′0 × 1.′0 (4.68×4.68 kpc). The i-th contour corresponds to $[\sqrt{2}]^i$ times 5 K km s^{-1} . Galaxies are from left to right NGC 4192, 4212, 4254, 4303, 4402, 4419, 4501, 4535, 4536, 4548, 4569, 4579, 4654, and 4689.

Galaxies with S0 type were excluded. Interacting galaxies were excluded. Peculiar galaxies in optical images were excluded. Galaxies observed with the NMA since 1994 were excluded. We have thus observed 15 galaxies, among which 14 galaxies were successfully mapped and are shown in Fig. 1, where the typical angular resolutions are $\sim 3''$.

3. Molecular Gas Morphology

The molecular gas distributions show a wealth of variety, although the galaxies have been selected from the brightest CO galaxies from Kenney and Young's (1988) sample without any bias. We can find some characteristic types in the central gas distributions:

Central/Single peak: The majority of the galaxies show a high concentration of molecular gas around the nuclei, which we call the "center/single peak" type. Fig. 3 shows the CO intensity distributions in the central $20'' \times 20''$ regions (1.6 kpc square) for single-peak galaxies. They are not correlated with stellar bars. Some new mechanism other than bar-induced inflow would be responsible for the accretion.

Twin peaks: An example is seen for NGC 4303, which shows two offset arms along the optical bar extending from a molecular ring with two peaks. In so far as the present data set is concerned, this type is not a majority.

Spiral arm type: Some galaxies have prominent spiral arms of molecular gas, mostly along optical dark lanes. NGC 4254 is a typical example.

Bar type: In some galaxies, extended bar-like features are found in the CO distributions. as for CO. NGC 4303. Molecular bar can be also seen in a galaxy without bar in optical bands such as in NGC 4254.

Amorphous type: Some galaxies do not show any regular gas distribution classified in the above types; we classify these galaxies in amorphous type. NGC 4689 is in this type, which has neither particular arms nor central peak. The CO intensities are very weak.

4. Rotation Curves and Dynamical Mass

Rotation curves (RCs) are the basic tool to obtain mass distributions in disk galaxies. We have argued for the advantage to use the CO line for many reasons (Sofue et al. 1999; Sofue and Rubin 2001). In order to solve the central rotation properties, we have developed a new iteration method, which determine the RC so that it reproduces the observed position-velocity diagram (Takamiya and Sofue 2002). We used the obtained position-velocity diagrams along the major axes across the nuclei, and applied this new iteration method.

Fig. 4 shows the PVDs, resulting RCs by the iteration method, and reproduced PVDs by convolution with the intensity distributions. In most cases, the convolved PVDs well mimic the observations.

Fig. 5a shows the calculated SMDs using the RCs obtained in Fig. 4 and combined with those from the literature for outer disks using the method developed by Takamiya and Sofue (2000). The SMDs appear to show a basic, principal structure as the following.

(1) Central massive core: In all cases the mass is highly peaked at the cen-

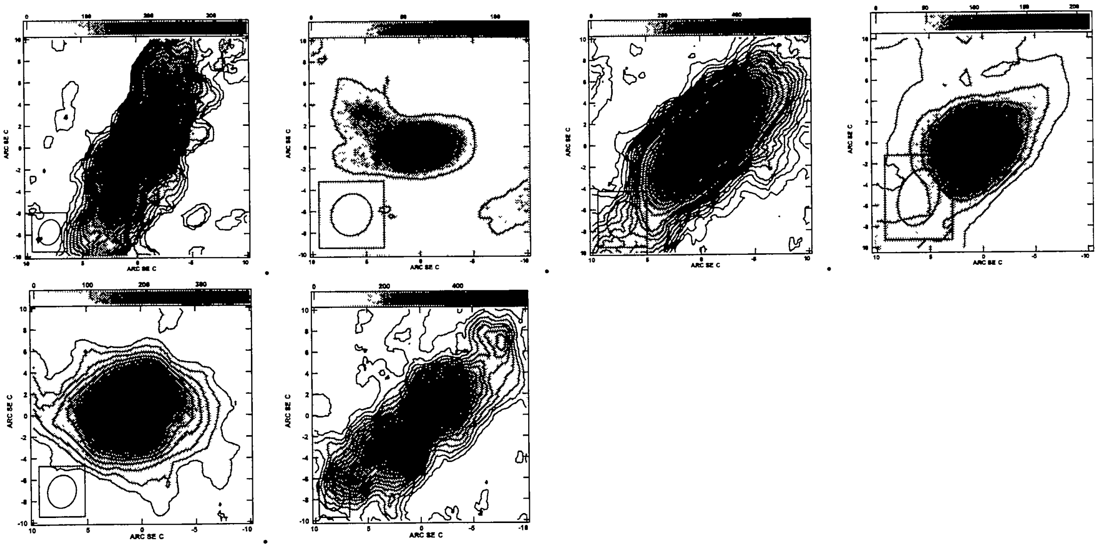

Figure 2. I_{CO} distributions in the central 20″ regions of the "central/single-peak" galaxies. NGC 4192, 4212, 4419, 4501, 4535, 436.

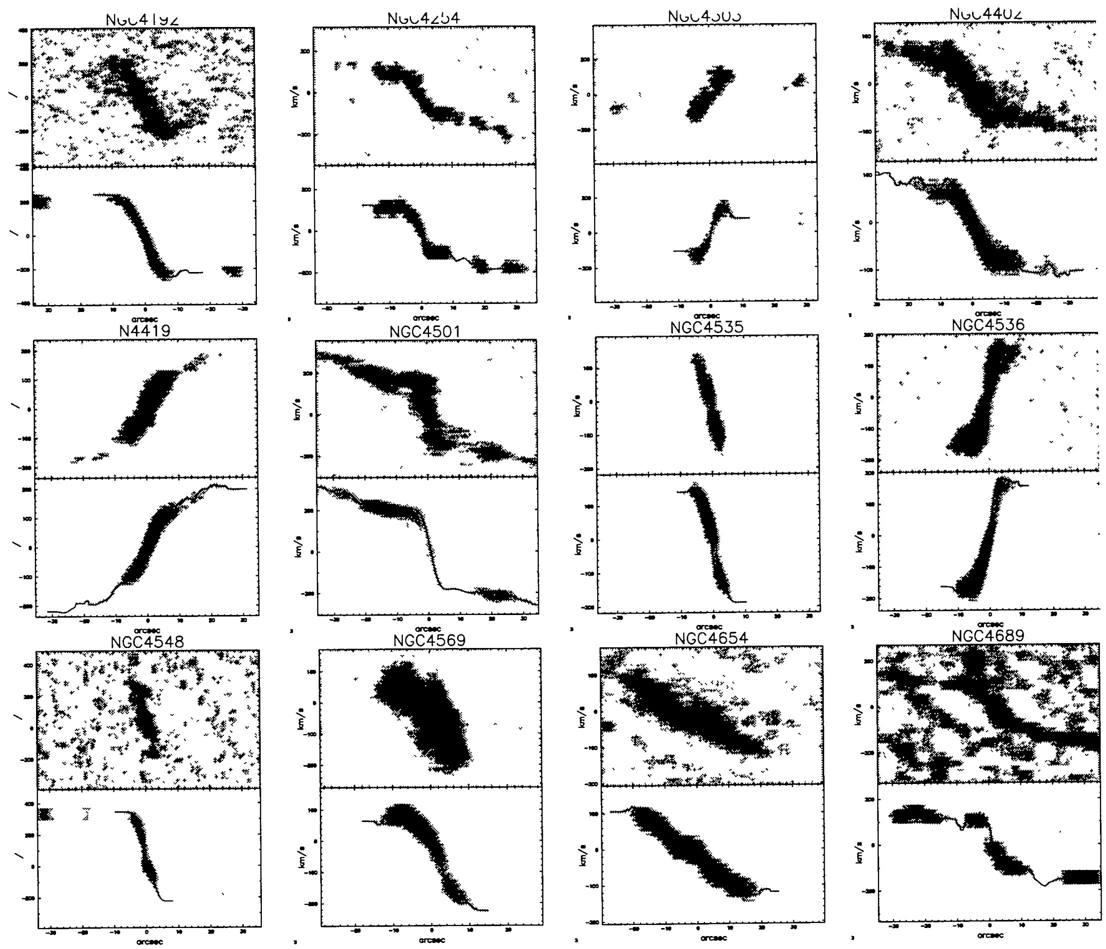

Figure 3. Observed PVDs along the major axes after correcting for the inclination of galaxy disks (upper panels), rotation curves by the iteration method (lower panels), and reproduced PVDs

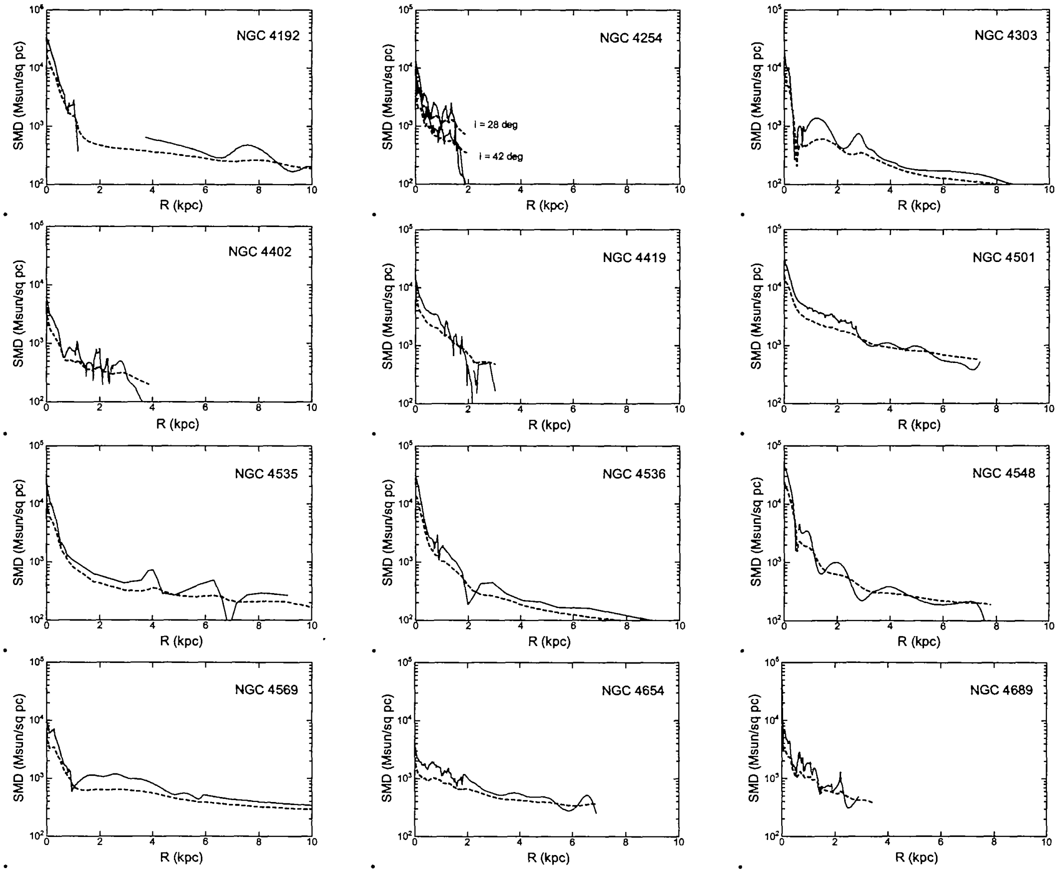

Figure 4. Radial profiles of the SMD of the Virgo spirals. Full lines for spherical symmetry assumption, and thick dashed lines for flat-disk assumption.

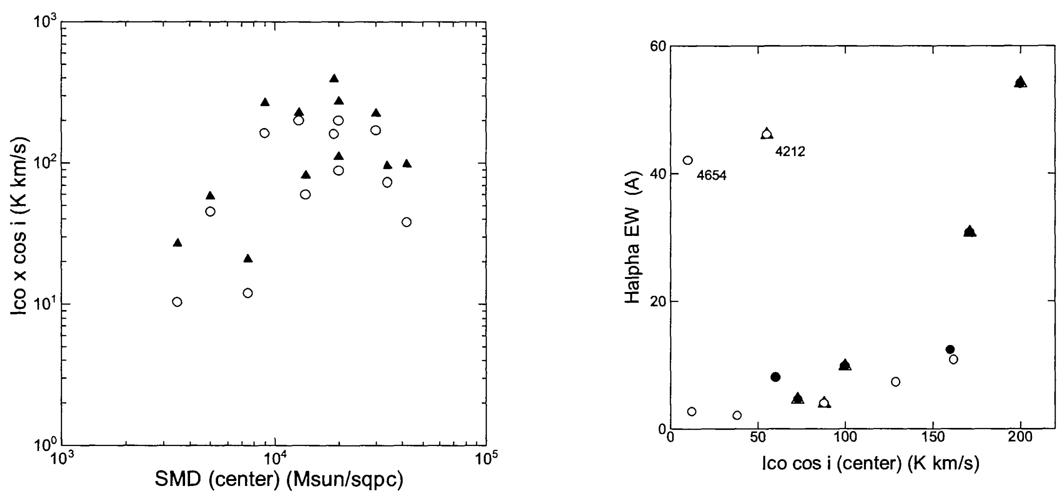

Figure 5. (a) Peak and center $I_{\rm CO}$ vs center SMD (triangles and circles, respectively.) (b) Central Hα activity vs. $I_{\rm CO}$.

ter, showing a core component with scale radius of about 100 to 200 pc with $\sim 10^4 - 10^5 M_\odot \mathrm{pc}^{-2}$. The dynamical mass of this component within 100 to 200 pc radius is of the order of $\sim 10^9 M_\odot$.
(2) Bulge: The SMD is followed by a more gradually decaying profile at $r = 0.2 - 2$ kpc with scale radius of 500 pc, due to the central bulge.
(3) Disk: The radial profiles at $r \gtrsim 2$ kpc are exponential representing the disk.

5. Correlation among SMD, $I_{\rm CO}$ and Activity

The unambiguous Cepheid distance of 16.1 Mpc enables us to compare the results without suffering from linear scales. We, thus, examined some correlations of the SMD with other parameters. Fig. 5a shows that there is a clear trend that the higher is the SMD, the higher is the peak and central CO intensities. The $I_{\rm CO}$ - SMD correlation indicates simply that *the deeper is the central potential, the stronger is the gas concentration.* This is consistent with our recent results for NGC 3079 (Koda et al. 2002).

Another remarkable correlation is the central activity seen in Hα equivalent widths (Ho et al. 1997) plotted against center $I_{\rm CO}$ in Fig. 5b, where the following activity cycle can be traced. The nuclei gradually get active with increasing $I_{\rm CO}$ from bottom-left corner of the figure, and the activity gets drastically settled when $I_{\rm CO}$ exceeds a threshold of about 150 K km/s to top-right. After exhausting the gas, activity still continues high, with the trajectory returning to top-left.

References

Ferrarese, L., Freedman, W. L., Hill et al. 1996, ApJ, 464, 568
Ho, L. C., Filippenko, A. V. & Sargent W. L. W. ApJS, 112, 315
Kenney, J. D. & Young, J. S. 1988, ApJS, 66, 261
Koda, K., Sofue, Y., Kohno, K. et al. 2002, ApJ, 573, 105
Sofue, Y., Koda, J., Nakanishi, H. et al. 2003a, PASJ, submitted
Sofue, Y., Koda, J., Nakanishi, H., & Onodera, S. 2003b, PASJ, submitted
Sofue, Y. & Rubin, V. C. 2001, ARAA, 39, 137
Sofue, Y., Tutui, Y., Honma, M. et al. 1999, ApJ, 523, 136
Takamiya, T. & Sofue, Y. 2000, ApJ, 534, 670
Takamiya, T. & Sofue, Y. 2002, ApJ, in press