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# High-Velocity Rotation in the Nuclei of Galaxies and Central Massive Cores

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**Abstract.** We present the results of a high-resolution (1-2") $^{12}$CO ($J = 1-0$)-line survey of the central regions of Virgo spirals using the Nobeyama mm-wave Array (NMA). By applying the newly-developed iterative method to position-velocity diagrams, we derive most reliable rotation curves. The obtained rotation curves generally show very high-velocity rotation in the central 100 pc, indicating massive cores of the order of $10^9 M_\odot$ within 100 pc. We discus possibilities of dark matter cusp in the nuclei and multiple components of the dark matter distribution in galaxies. We comment about possible future CO-line works on high-z galaxies using ALMA on the basis of our extensive CO-line survey of low-z galaxies.

## 1. Introduction

We have emphasized that the CO molecular lines are useful to derive accurate rotation curves in the central regions of spiral galaxies, because of the high concentration of molecular gas in the center as well as for negligible extinction of the lines through the galactic disks (Sofue 1996, Sofue et al 1997, 1998, 1999). CO-line rotation curves generally generally show a very steep rise of the central rotation velocity within $\sim$ 100 pc, and often non-zero velocities at the nuclei.

The CO observations are complimentary to recent high-dynamic-range CCD spectroscopy of in optical lines, which also makes it possible to obtain high accuracy rotation curves in the central regions (Rubin et al 1997; Bertola et al 1998). However, in general, optical lines suffer from significant extinction by the central dusty disks, which is particularly significant for highly-inclined and edge-on galaxies. Hence, the CO lines will be the most appropriate tool to investigate the central kinematics of spiral galaxies, if the angular resolution is sufficiently high.

In order to obtain high-accuracy CO-line rotation curves for the central regions of normal spirals, we have performed a long-term project to observe Virgo-cluster spirals using the Nobeyama mm-wave Array (NMA) in the CO $J = 1 - 0$ line. In this paper, we present some results from this CO survey, and discuss the general properties of central rotation kinematics based on the high-accuracy rotation curves.

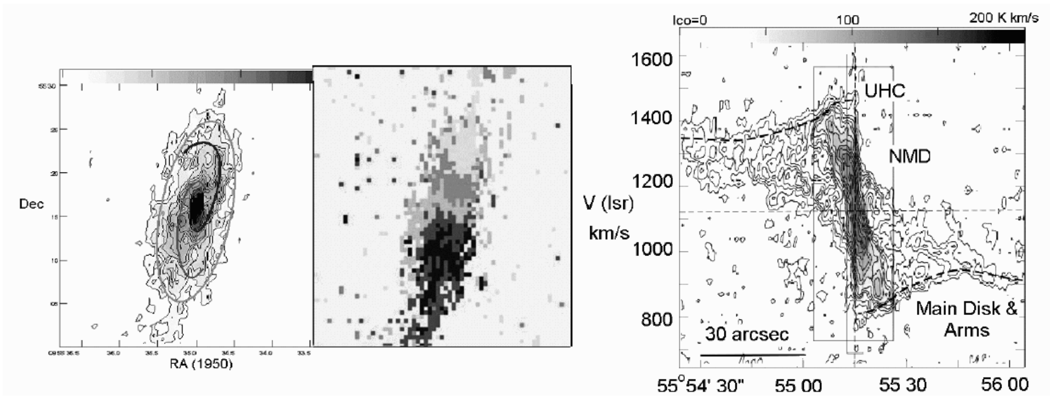


Fig. 1. (a) (left panel) Integrated CO line intensity of NGC 3079 as obtained by the Nobeyama mm-wave Array combined with the 45-m telescope. (b) (middl) Velocity field of NGC 3079 in the same scale as in (a). (c) (right) Position-velocity diagram along the major axis at resolutions of $1''6 \times 1.4''$. The rotation velocity does not decline to zero at the nucleus, but remains always at finite value. UHC stands for ultra-high-density molecular core, and NMD for nuclear molecular disk. $1''$ corresponds to 75 pc.

## 2. High-resolution CO Observations at Nobeyama

In order to see if the central steep rise, or more likely non-zero rotation velocity at nuclei, is indeed the case at higher resolutions than the current observations, we have performed interferometer observations at Nobeyama in the $^{12}$CO ($J = 1{-}0$) line of nearby CO-rich galaxies.

### 2.1. NGC 3079

The highest, most sensitive observations were obtained for the edge-on galaxy NGC 3079 (Sofue et al 2001). The $^{12}$CO (1 - 0) observations of NGC3079 were made in January to April 2000 using the 7-element mm-wave interferometer at Nobeyama, which consisted of the 6-element mm-wave array in A configuration linked with the 45-m telescope, called the Rainbow mode. We also obtained C and D-compact array observations, and all UV data were combined. The synthesized beam was about $2''$ for the natural weighting using all the configuration, and was $0''.9$ for uniform weighting for the Rainbow array alone. Fig. 1 shows the integrated intensity map and velocity field of NGC 3079.

The CO line intensity distribution in NGC 3079 is summarized as follows: (a) An ultra-high-density compact and massive molecular core (UHC) of radius 125 pc and molecular mass of $3 \times 10^8 M_\odot$ is detected at the nucleus. (b) The core is embedded in a warped nuclear molecular disk (NMD) of radius 900 pc, and the disk has two spiral arms. (c) An outer disk extending for more than 2 kpc along the major axis.

The right panel in Fig. 1 shows a PV diagram for the central region of NGC 3079, where the central ultra-high density molecular core (UHC) and the nuclear molecular disk (NMD) are resolved out both in the velocity and space. The UHC shows up as an intense PV ridge near the center. The rotation velocity of the molecular core increases toward the nucleus, and the velocity does not decline

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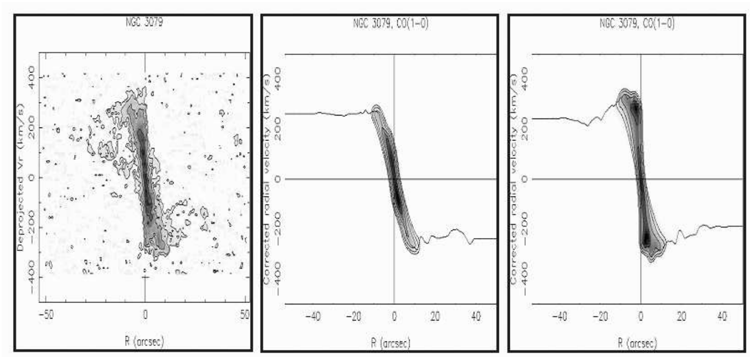


Fig. 2. (a) (Left panel) Observed position-velocity diagram of NGC 3079 along the major axis. (b) (middle) PV diagram constructed from a rotation curve obtained by the peak-intensity tracing technique (thick line). (c) (right) PV diagram constructed from the most reliable rotation curve (thick line) obtained by our new method as described in the text (Takamiya and Sofue 2001, private communication).

to zero at the center, indicating that the rotation curve starts from a finite value already at the center with at about 300 km $s^{-1}$ or greater. The warped nuclear disk shows up as an inclined ridge in the PV diagram, representing two-armed spiral arms. The radius of this disk component is $\pm 12''$, or the total radius is about $\pm 900$ pc. The main disk of the galaxy in the PV diagram shows up as two fainter ridges with smaller relative velocities, bifurcating from the main ridge of the nuclear disk. These bifurcated ridges show roughly rigid rotation, but at slower velocities, which represents foreground/background spiral arms. Fig. 2 shows a PV diagram used to derive the most reliable rotation curve using the new iterative method as described below.

### 2.2. The Nobeyama CO-line Survey of Virgo Galaxies

In the long-term project with the Nobeyama mm-wave Array (NMA) in 1999, 2000 and 2001, we have obtained high-angular resolution CO J=1-0 line observations for about 20 CO-richest Virgo galaxies. The galaxies were selected from Kenney and Young's (1988) list of CO survey of Virgo galaxies in the order of their CO integrated intensities. Among them, AB, C and D array configuration observations were completed for 10 galaxies by the spring of 2001. Fig. 3 shows the obtained CO intensity maps for eight galaxies with a common linear scale. Fig. 4 shows PV diagrams along the major axes for the eight galaxies shown in Fig. 3, on which the most reliable rotation curves are superposed by the thick lines, as obtained by the iterative method.

CO intensity maps in Fig. 3 show that all the galaxies displayed here have high-density concentrations of molecular gas in the nuclei, in addition to various diffuse structures surrounding the center. Since the sample galaxies were selected by their total CO-line luminosity, but not by their intensity distributions, the present result indicates that CO-rich galaxies generally contain high-density molecular structures within $\sim 1$ kpc region of their nuclei.

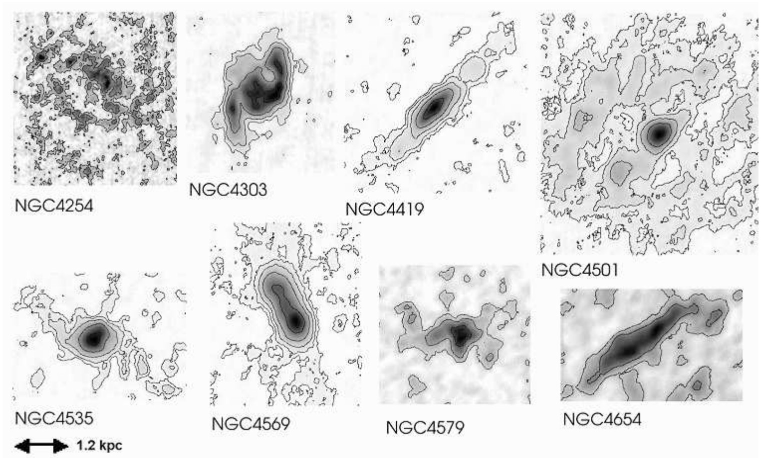


Fig. 3. CO integrated intensity maps of the Virgo spiral galaxies observed with the Nobeyama mm-wave Array in the course of the long-term project at Nobeyama 1999 - 2001.

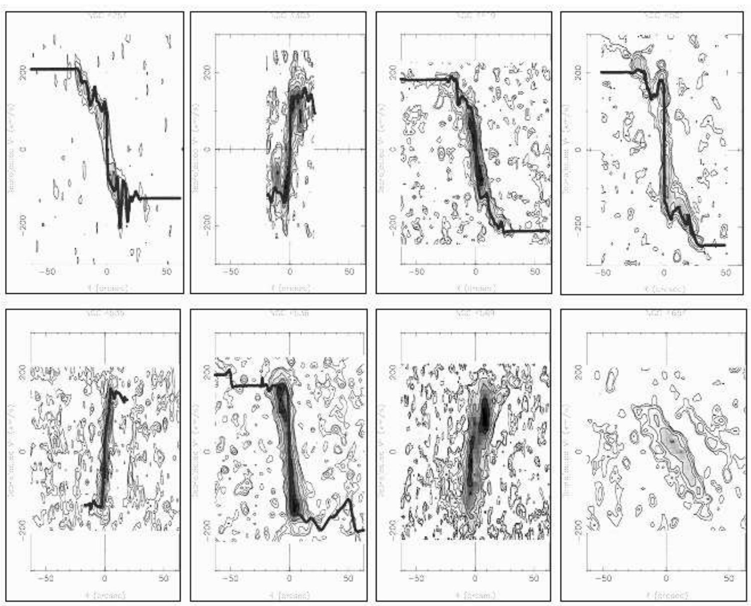

Fig. 4. PV diagrams along the major axes of the Virgo galaxies shown in Fig. 3. Thick lines indicates the most reliable rotation curves obtained by the iterative method.

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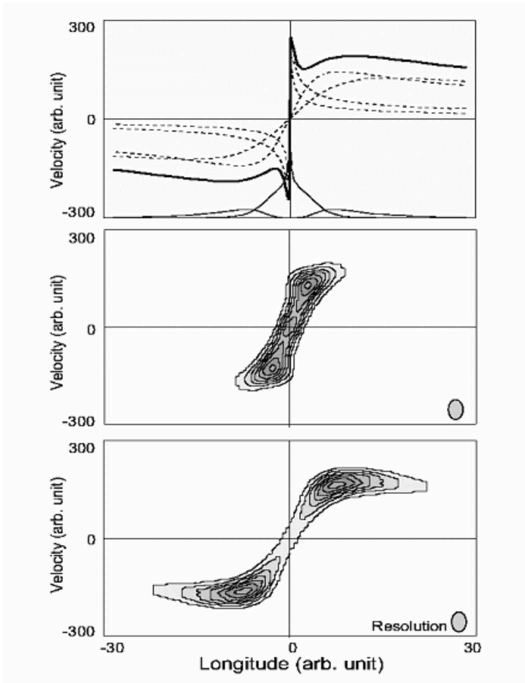


Fig. 5. Simulation of PV diagrams from the assumed rotation curve and gas distribution as given in the top panel. The middle panel shows a simulated PVD for CO lines, and the bottom for HI line.

The PV diagrams in Fig. 4 reveal again steep rise of rotation velocity within the central $\sim 100$ pc, and often the velocities do not decline to zero at the nuclei, except for NGC 4654, which exhibits more gentle rise. The rotation curves fitted to the PV diagrams by the iteration method as described in the next section, drawn by the thick lines, show more clearly that the rotation rise in the nuclei is extremely steep. These results confirm the currently proposed nuclear massive cores in spiral galaxies, which have as high mass as $M_{\rm core} \sim rV_{\rm rot}^2/G \sim 10^9 M_\odot$ for $r \sim 100$ pc and $V_{\rm rot} \sim 200$ km s$^{-1}$.

## 3. New Method to Derive Rotation Curves: Iteration Method

### 3.1. Current Methods

Rotation curves have been usually obtained from position-velocity diagrams (PVD) along the major axes of galaxies. There have been several methods, such as the peak-intensity tracing method, weighted-mean velocity method, and the envelop-tracing method [see Sofue and Rubin (2001) for detailed description of the methods]. These methods are usually valid for the flat-rotation regions, but are often too crude to describe the central velocities. Fig. 5 demonstrates how easily is the central high-velocity rotation missed by honestly tracing the intensity peaks on a PVD.

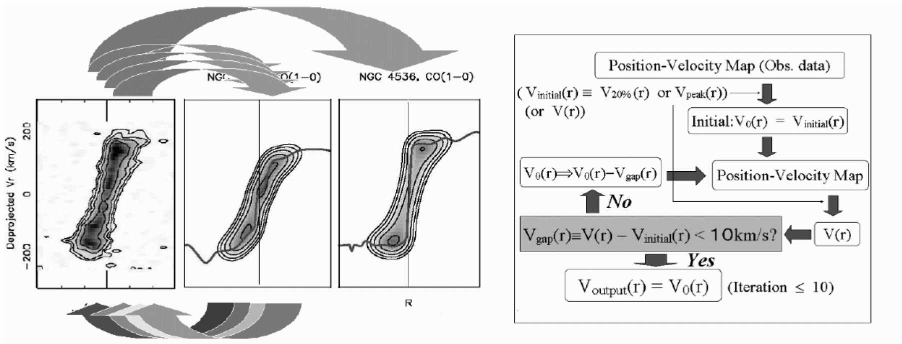


Fig. 6. The iterative method to derive the most reliable rotation curves from PV diagrams.

### 3.2. Iterative Method

Takamiya and Sofue 2001 (private communication) have developed a new method, called the iterative method, to derive a rotation curve. This extremely reliable, and probably ultimate, method comprises the following procedure, as illustrated in Fig. 6. An initial rotation curve, RC0, is adopted from a PV diagram (PV0), obtained by any simple method, e.g. by a peak-intensity method. Using this rotation curve and an observed radial distribution of intensity of the line used in the analysis, a PV diagram, PV1, is constructed. The difference between this calculated PV diagram and the original PV0, e.g. the difference between peak-intensity velocities, is used to correct the initial rotation curve to obtain a corrected rotation curve, RC1. This RC is used to calculated another PV diagram PV2 using the observed intensity distribution, and to obtain the next iterated rotation curve, RC2 by correcting for the difference between PV2 and PV0. This iteration is repeated until PV$i$ and PV0 becomes identical, such that the summation of root mean square of the differences between PV$i$ and PV0 becomes minimum and stable. RC$i$ is adopted as the most reliable rotation curve. Fig. 2 and 4 show the most reliable RCs obtained by applying this method to the observations of NGC 3079 and the Virgo-CO survey galaxies.

## 4. Universal Properties of Rotation Curves : Central High Velocities and Massive Cores

From the rotation curve database of Mathewson et al (1996), Persic et al (1996) have well described the universal properties of rotation curves for the disk and outer regions of galaxies. On the other hand, in order to describe general properties of inner and central rotation curves, we need higher resolution rotation curves such as those in the present works.

In Fig. 7 we reproduce well-sampled rotation curves obtained by combining CO, CCD H$\alpha$, and HI observations from our current study (Sofue et al 1999). From the presently obtained high-accuracy rotation curves, particularly from the case for the highest-quality rotation curves for NGC 3079, we may summarize the universal properties of rotation curves as follows.

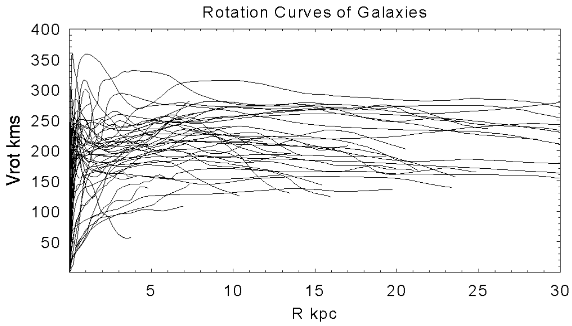


Fig. 7. High-accuracy rotation curves of Sb, Sc, SBb and SBc galaxies (Sofue et al. 1999).

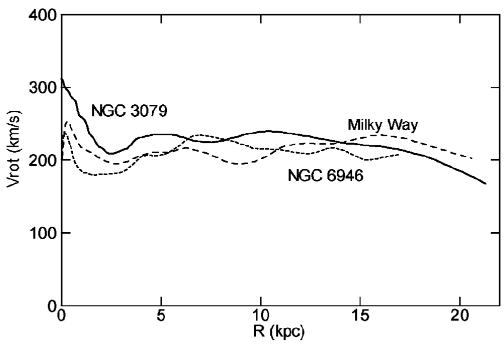


Fig. 8. Rotation curve of the edge-on galaxy NGC 3079, compared with those of the Milky Way and NGC 6946.

(1)Massive galaxies generally show very steep rise of rotation in the central region. Mostly likely, the rotation velocity starts from a finite value at the center, indicating a massive core at the nucleus. (2) Small-mass galaxies with slower rotation velocities, however, tend to show more gentle rise. (3) The central rotation is followed by a central peak and/or shoulder corresponding to the bulge. (3) RC is then followed by a road maximum in the disk. (4) The outer RC is flat, and sometimes declining toward the edge.

Using the PV diagram, we derived a central rotation curve, and combined it with the existing data (e.g. those from Irwin and Seaquest 1991) to obtain total rotation curve as shown in Fig. 8. The rotation velocity starts from a finite value of about 300 km $s^{-1}$, and declines to a first minimum of about 200 km $s^{-1}$ at $30''$ (2.5 kpc) radius. It is then followed by a broad disk maximum of $V \sim 240$ km $s^{-1}$at 5 to 10 kpc, and then by a declining outermost rotation.

Using the rotation curve, we can derive a differential surface mass density as a function of radius by applying the method developed by Takamiya and Sofue (2000). The result for NGC 3079 is shown in Fig. 9. The surface mass density (SMD) increases steeply toward the center, indicating high density cores with $SMD > 10^5 M_\odot$ pc$^{-2}$. Since NGC 3079 is an Sc galaxy with a poor central bulge, the high mass density could infer a concentration of invisible (dark) mass in the central region.

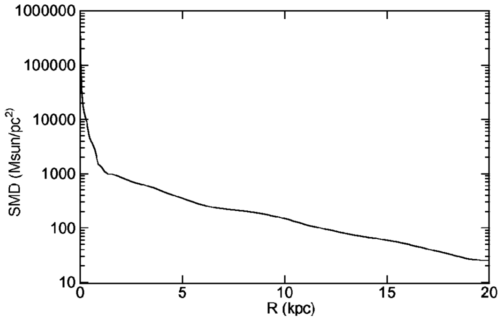


Fig. 9. Surface-mass density as a function of the radius for NGC 3079. Extremely dense, massive core is found in the central 100 pc region.

## 5. Condluding Remarks

We have presented a high-resolution CO line survey of the Virgo spirals using the Nobeyama mm-wave Array (NMA). Central rotation curves as obtained by our newly developed iterative method indicates extremely steep rise of rotation velocity in the nuclei, showing the existence of massive cores of the order of $10^9 M_\odot$ within 100 pc in most of the sampled galaxies.

Future works include obviously study of mass-to-luminosity ratio by comapring the dynamical surface mass density from the rotation curves with near IR surface photometry obtained with IR telescopes such as SUBARU. Detailed M/L study would contribute to detailed information of dark matter, such as those expected from of dark matter cusp theory in the nuclei and/or multiple dark components in a single galaxy. We finally comment that the present CO-line study of detailed central kinematics of nearby galaxies and clusters of galaxies, particularly the mass distribution from rotation curves, would be continuously extended to future works on dynamical evolution of high-z galaxies using ALMA, Atakama Milimeter and submilimeter Array under construction.

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