Proceedings of the International Conference at Ishigaki, 2006 June, on
"Mapping the Galaxy and Galaxies", ed. K. Wada.

CO-Line Rotation Curves, Deep Potential of Massive Cores, and High-density Molecular Nuclei

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Summary. We review observational studies of central rotation curves of spiral galaxies using the Nobeyama mm-wave interferometer in the CO 2.6-mm line emission. The observed high-accuracy rotation curves show universal characteristics: RCs rise steeply in the nuclei, or they start at finite speed, and are flat toward the galaxy edges. Calculated mass distributions are similar to each other: spiral galaxies generally have a massive core of $\sim 10^9 M_\odot$ in the central 100 pc, bulge, disk and a dark halo. We found extremely high-density, single-peaked molecular gas nuclei in many galaxies, which are embedded in deep gravitational potential of the massive core. Although the molecular nuclei is as dense as that of a giant molecular cloud, the gas is kept gravitationally stable because of the high-velocity rotation.

1 Introduction

Mass distributions in the disk and massive halos of spiral galaxies have been derived by rotation curves[1]. However,, the mass structure within bulge and that in the circum-nuclear regions are not well investigated, mainly because of the lack of accurate rotation curves in the central hundred parsecs.

In order to obtain central rotation curves, we need high spatial resolution as well as particular spectral lines that are not contaminated by the bulge light and interstellar extinction. The CO line emission is ideal for this purpose: (1) the CO line is transparent from interstellar dust extinction; (2) CO line is strongest in the central 1 kpc because of high molecular gas concentration; (3) the intrinsic line width is narrow because of low temperature and low velocity dispersion of molecular gas, and hence, radial velocities reflect rotation of the disk better than optical lines emitted by higher-temperature components; (4) high angular resolution is achieved by using mm-wave interferometers; (5) high velocity resolution is achieved by molecular line spectroscopy; and (6) high sensitivity is obtained by using large-aperture antennae.

High sensitivity interferometer CO-line surveys have been, thus, obtained by using OVRO, BIMA, PdB, and Nobeyama mm-wave Arrays [2, 3, 4, 5].

We have performed a CO ($J = 1 - 0$) line survey of Virgo and nearby spirals using the Nobeyama mm-wave Array (NMA) in order to obtain high-accuracy central rotation curves[6, 7, 8, 9, 10].

2 Rotation Curves and Universal Mass Distribution

We observed fifteen Virgo spirals of normal Sb and Sc types. The reasons why we chose the Virgo galaxies are: that (a) the distance is well determined from Cepheid calibration to be 16.1 Mpc[11]; that (b) galaxies with a variety of types are available at the same distance, (c) a wealth of data sets in other wave ranges are available from the literature, and that (d) Virgo galaxies are visible from ALMA for a more detailed studies in the future based on the present data will be possible.

2.1 Iteration method

In order to obtain accurate rotation curves, we applied the iteration method, which was developed for deriving RCs as accurate as possible from observed data, so that resultant RCs can reproduce observed PV diagrams, as illustrated in figure 1[12, 7]. Some obtained examples for the Virgo galaxies are shown in figure 2.

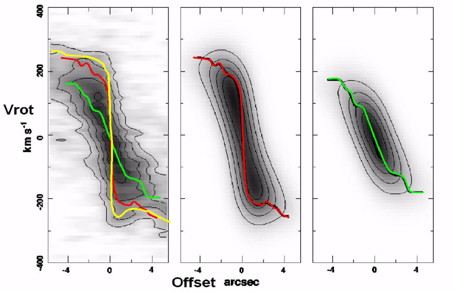

Fig. 1. Iteration method to derive a rotation curves from position-velocity diagram.

2.2 Rotation curves

The obtained rotation curves of the Virgo galaxies are shown in figure 3a. All RCs have the same characteristics: the rotation speed increases very steeply within a few tens of parsecs of the nuclei, or more appropriately, the rotation velocity starts from a finite value from the nucleus. Then, the rotation velocity remains almost constant till the edges of galaxy disks. This characteristic is

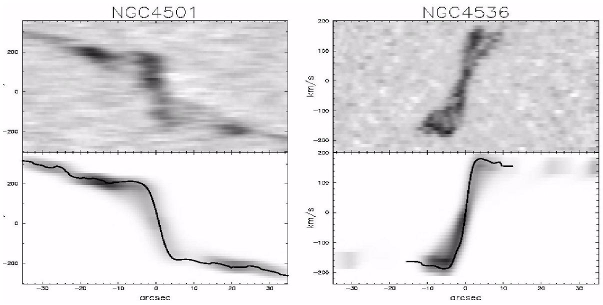

Fig. 2. (a) Observed PV diagrams for two Virgo spiral galaxies (top). (b) Derived rotation curves by iteration method, and reproduced PV diagrams by convolving with the observed intensity distribution (bottom).

commonly observed for nearby spiral galaxies with high-accuracy rotation curves (figure 3b).

As the central rotation curves gets more and more precisely determined such as by using high-resolution interferometers as the present case, it is needed to display an RC in a way so that its nuclear behavior is more appropriately represented. This is particularly crucial for studying the mass structure inside bulges in connection to the central black holes. For this purpose, we proposed a logarithmic rotation curves (LRC), as shown in figure 3c. In this logarithmic display, the central high velocity rotation and its connection to the Keplerian law around the black holes are well traced. However, the number of galaxies with such LRC is still limited for observations of velocity structure within an arcsec or subarcsec. Deriving better logarithmic rotation curves and related study of mass distribution in the circum black hole region will be a subject for the future using higher resolution facilities like ALMA.

3 Universal Mass Distribution

Once rotation curves are obtained, we are able to calculate the mass distribution. We have calculated surface mass densities (SMD) by assuming two extreme cases: one for a spherical case, another for a thin disk[13]. Both sphere and disk assumptions give almost the same results within 50% difference except for outer regions, where the sphere assumption loses accuracy for the edge effect.

Figures 4a and 4b show calculated SMD distributions for the whole disk and inner regions of NGC 4536. The mass is highly concentrated in the central 100 pc region, where SMD reaches a value as high as $\sim 10^5 M_{\odot}\mathrm{pc}^{-2}$, composing a distinguished mass component of total mass $\sim 10^9 M_{\odot}$, which we call the central massive core. The core is then followed by a bulge component, obeying an exponentially decreasing function with a scale radius of about 0.5 kpc. The

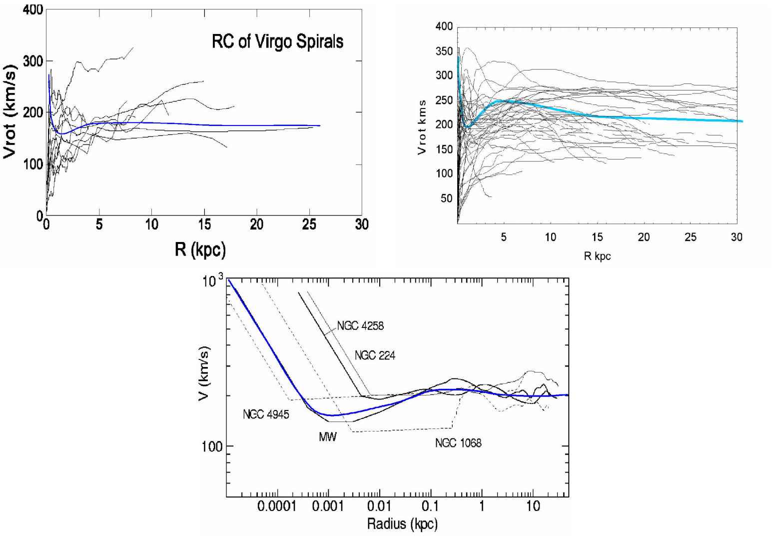

Fig. 3. (a) Rotation curves of Virgo (left) and (b) nearby (right) spiral galaxies. (c) Logarithmic RCs are shown in the bottom panel. Thick lines illustrate typical behavior of the rotation curves.

bulge is surrounded by an exponential disk of a scale radius of 5 kpc, which is followed by a largely extended dark halo with scale radius greater than 10 kpc. The thick lines schematically indicate these individual components.

The presently obtained mass distribution has been found to be common to all the galaxies including the Virgo as well as the nearby galaxy samples. Namely, the galactic mass distribution can be represented by a fundamental structure comprising a central black hole, a massive core, a bulge, a disk, and a dark halo. This structure appears to be universal, applying even for such irregular galaxy like the Large Magellanic Cloud (figure 5)[14].

4 High-density molecular nuclei

High resolution CO data are useful not only for the dynamics and mass, but also for central interstellar physics such as the gas density distribution. One of the interesting facts we noticed was highly concentrated molecular peaks in the nuclei of several sample galaxies (figure 6).

5 Single Peaks

A high density molecular core was known for NGC 3079[15, 16], which has been thought to be a peculiar case in contrast to more general molecular rings

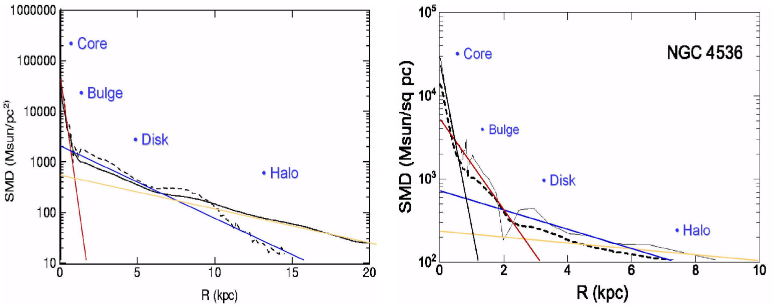

Fig. 4. Typical surface mass density distribution, as observed for the spiral galaxy NGC 4536. Note the existence of a massive core of 100 pc radius with extremely high mass density.

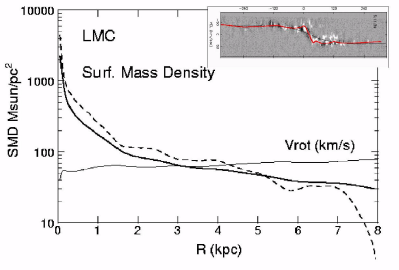

Fig. 5. Rotation curve and mass distribution in the Large Magellanic Cloud. Note the central mass concentration, where no optical counter part is visible: There appears to be a dark bulge.

and/or twin-peaks. However, we noticed that centrally peaked molecular peaks are not an exception, but is more generally found than twin peaks: We found five single peaks (NGC 4192, 4212, 4419, 4535, 4536), one semi-single peak (NGC 4501), one twin peaks (NGC 4303) and one ring (NGC 4569) among our fifteen Virgo spirals. Hence, single peaks are more common than twin peaks within the present resolution of ∼ 100 pc.

In order to investigate the density distribution in and around the single peaks, we used uniform weighting for UV plane of interferometer data analysis to obtain higher resolution maps ($\sim 1''$ resolution) as shown in figure 7. The central intensities indicate that the single peaks have face-on column densities of $N_{\mathrm{H}_2} \sim 10^{22} - 10^{23}\mathrm{H}_2\mathrm{cm}^{-2}$, or surface gas mass density $\Sigma_{\mathrm{gas}} \sim 10^2 - 10^3 M_{\odot}\mathrm{pc}^{-2}$. Here, we assumed a conversion factor of $1.0 \times 10^{20}\mathrm{H}_2\mathrm{cm}^{-2}/\mathrm{K\ km\ s}^{-1}$. Since the gas is strongly peaked in the center, having very high density, we call these peaks molecular nuclei.

In figure 8 we plotted the CO intensity of the molecular nuclei against dynamical surface mass density (SMD), where triangles denote plots for high

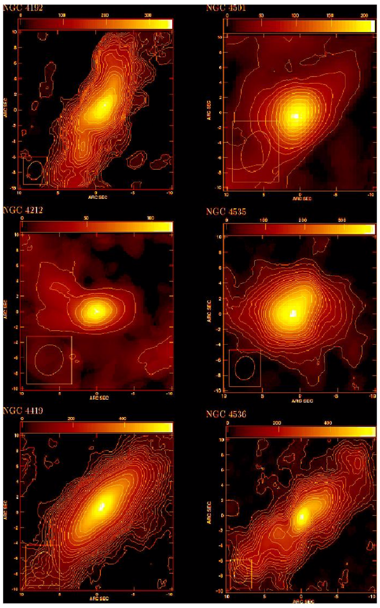

Fig. 6. CO intensity distributions for single peak galaxies at 4-5$''$ resolution.

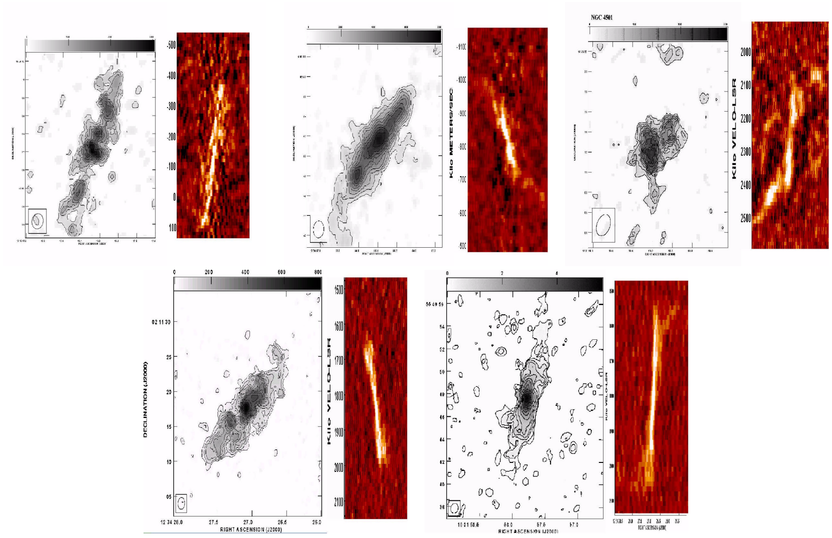

Fig. 7. CO intensity distributions and PV diagrams for the Virgo single peak galaxies NGC 4192, 4419, 4501 (semi-s-peak), 4536, and the typical single peak NGC 3079 at high resolution $\sim 1''$

resolution analysis with uniform weighting (resolution $\sim 1''$) and circles for natural weighting (resolution $\sim 4''$). The solid line indicates a gas mass equal to 1.5% of the dynamical mass.

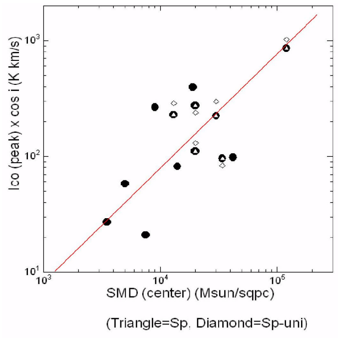

Fig. 8. CO intensity ($I_{\rm co}$) of molecular nuclei plotted against surface mass density (SMD). The solid line indicates the gas mass is 1.5 % of dynamical mass for a conversion factor of 1.0×10^{20}H$_2$cm^{-2}/K kms^{-1}.

5.1 Stability

The high column density of the single peak molecular cores indicates a very high spatial gas density of $n \sim 10^3 - 10^4$H$_2$cm^{-3}, if the thickness is several tens of parsecs as in the case of the Milky Way center. This density is comparable to giant molecular cloud. Now, a question arises why such high density gas is stable against gravitational instability for star formation.

Toomre's Q value is defined by $Q = \Sigma_{\rm c}/\Sigma$, where $\Sigma_{\rm c} = \kappa c/\pi G$, $\Sigma = SMD_{\rm gas}$, $\kappa \sim 2$ ~ 0.5My^{-1} is the epicyclic frequency with being the rotational angular velocity, and $c \sim 30$km s^{-1} is the velocity dispersion. Then, we have $\Sigma_{\rm c} = 5 \times 10^3 (V_{200} c_{30}/R_{100}) M_\odot {\rm pc}^{-2}$, where V_{200} is rotation velocity in unit of 200 km s^{-1}, and R_{100} is radius in unit of 100 pc, and c_{30} is velocity dispersion in unit of 30 km s -1. In the molecular cores, we obtain Q values as large $Q \sim 10 - 100$, and hence, the disk is gravitationally stable.

5.2 Formation of Molecular Nuclei

The molecular nuclei are thus gravitationally stable, and therefore, they stay in gas with secularly increasing density until the local gas density exceeds the threshold value $\Sigma_{\rm c}$. It is commonly accepted that the interstellar gas is accumulated by transferring its angular momentum to spiral arms and barred potentials through galactic shocks.

We may draw a possible scenario: The interstellar gas is gathered by two-armed shocked inflow along a bar, temporarily being accumulated on the bar end to form twin-peaked molecular concentration on a ring. Due to internal viscosity as well as to collisions with internal gas on other orbits, the gas is then gradually accumulated to the nuclear region. Since the gas disk is stable as discussed above for the large Q value, it sinks further into the circum-nuclear region to form a centrally peaked high-density molecular nucleus. The inflow will continue until the disk gets denser and gravitationally unstable, until starburst is triggered to exhaust the gas.

6 Summary

We have shown that rotation curves of Virgo and nearby normal spiral galaxies and the calculated mass distributions have the universal characteristics. The mass structure has the central black hole, massive core, bulge, disk, and dark halo. These components may not necessarily be distinguished from each other, but can be considered consist a continuous structure.

High resolution CO imaging revealed that many galaxies have single-peaked central gas concentration, which is more frequently observed than twin peaks and rings. The single peaks, which we called molecular nuclei, are shown to be gravitationally stable, and therefore, are long lived for them to grow to attain sufficiently high density.

Higher resolution mapping of the molecular nuclei and the dynamical structure from velocity information will be a subject to future molecular line observations using ALMA. The Virgo galaxies, well visible from ALMA, would be one of the most promising targets for the future rotation curve projects.

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