Formation and Evolution of Galaxy Disks
ASP Conference Series, Vol. 396, © 2008
J. G. Funes, S.J., and E. M. Corsini, eds.

Central Rotation Curves by CO Lines

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Abstract. Central rotation curves are fundamental to understand the mass distribution inside galactic bulges and central disks, which may be physically linked to central massive objects. We review observational studies of central rotation curves using mm-wave interferometers in the CO 2.6 mm line emission. Observed high-accuracy rotation curves show steep rise in the nuclei, or more likely, they start at finite speed from the center. Mass distributions show that spiral galaxies generally nest a massive core of $\sim 10^9$ $M_\odot$ in the central 100 pc, which is supposed to link the black hole and bulge. Massive cores are often associated with high-density molecular gas nuclei, and the core mass and gas density are proportional. The molecular nuclei are gravitationally stabilized by high velocity differential rotation in the deep gravitational potential.

1. Introduction

Rotation curves are the most fundamental tool to derive the mass distribution in disk galaxies, and have been studied in most detail in the decades by optical and radio line observations. Flat rotation was established for outer disks, indicating dark matter halo, exponential disk, and high-density concentration toward the center (Rubin et al. 1982; Bosma 1982; Mathewson et al. 1992; Persic & Salucci 1995; Sofue & Rubin 2001).

In the decade, inner rotation curves (RCs) were more precisely observed to show high-velocity rotation toward the nuclei (Bertola et al. 1998; Rubin et al. 1999; Funes et al. 2002). Since optical lines are often contaminated by strong bulge light and Balmer absorption lines, the mm-wave CO-line was realized to be an alternative and/or complimentary tracer of the central rotation (Sofue 1996; Sofue et al. 1999). The CO line is found to be a good tracer of galactic rotation: it is transparent from interstellar dust extinction; emission is strongest in the central 1 kpc because of high molecular gas concentration; 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; high angular resolution is achieved by using mm-wave interferometers; high velocity resolution is achieved by molecular line spectroscopy; and high sensitivity is obtained by combining interferometers with large dishes.

High-resolution CO-line surveys have been extensively obtained for nearby spiral galaxies using mm-wave interferometers such as the OVRO, BIMA, PdB, and Nobeyama mm-wave Array (Sakamoto et al. 1999; Schinnerer et al. 2002; Regan et a. 2001; García-Burillo et al. 2005). At Nobeyama, we performed a CO(1-0) line survey of Virgo and nearby spirals using the Nobeyama mm-wave

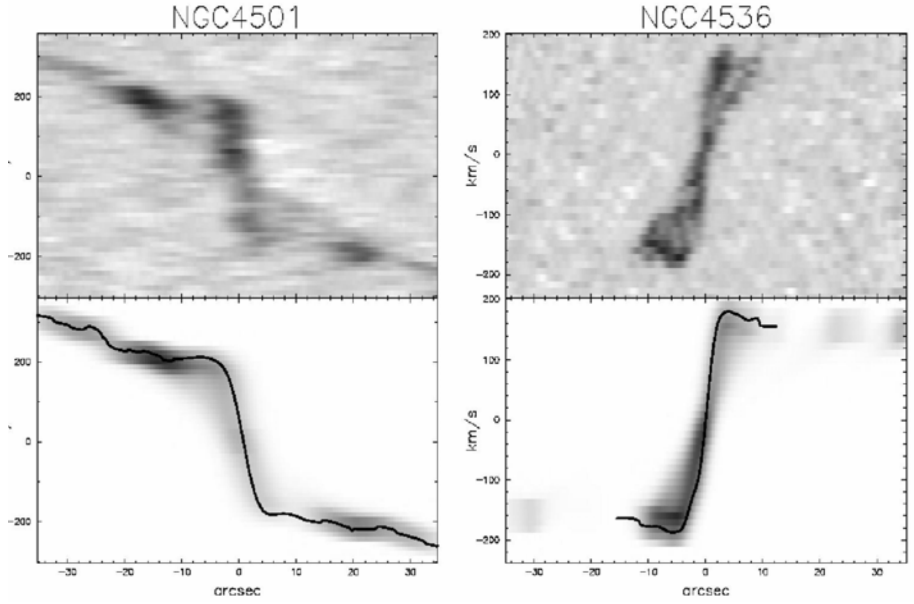

Figure 1. Observed PV diagrams for two Virgo spiral galaxies (top panels). Derived RCs by iteration method, and reproduced PV diagrams by convolving with the observed intensity distribution (bottom panels).

Array (NMA), and obtained high-accuracy central RCs (Sofue et al. 2003a,b; Onodera et al. 2004; Nakanishi et al. 2004; Koda & Sofue 2006). In this paper we review the results from the Nobeyama Virgo survey for the central rotations and mass distributions.

2. Position-Velocity Diagrams and Rotation Curves

In the survey fifteen Virgo spirals of normal Sb and Sc types were observed in the CO line at resolutions $\sim 3'' - 5''$. The reasons why we chose the Virgo galaxies are: that (a) the distance is well determined from Cepheid calibration to be 16.1 Mpc; 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. Fig. 1 shows examples of the observed CO position-velocity (PV) diagrams for the observed galaxies.

The PV diagrams can be used to obtain high-accuracy RCs by applying the iteration method, which iteratively derive RCs that can reproduce observed PV diagrams (Takamiya & Sofue 2002). The obtained RCs of the Virgo galaxies are shown in Fig. 2 and 3. All RCs show that the rotation velocity increases very steeply within a few tens of parsecs of the nuclei. The rotation velocity more likely starts from a finite value from the nucleus. Then, the rotation velocity remains almost constant till the edges of galaxy disks. This characteristic is commonly observed for nearby spiral galaxies with high-accuracy RCs).

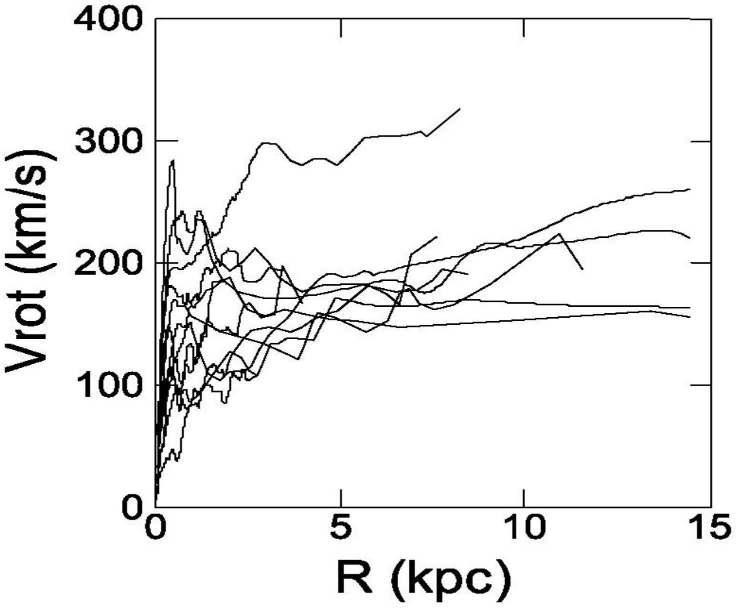

Figure 2. CO-line RCs of Virgo spiral galaxies, showing steep rise of rotation velocity in the central regions.

3. Massive Cores and Molecular Nuclei

Using a RC, we can calculate the surface mass density by assuming two extreme cases: one for a spherical case, another for a thin disk (Takamiya & Sofue 2000). 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.

The calculated surface mass density (SMD) distribution for NGC 4536 is shown in Fig. 3. We find that the mass is highly concentrated in the central 100 pc region, where SMD at the nucleus is as high as $\sim 10^5$ $M_\odot$ pc^{-2}. This component makes a distinguished mass concentration of a total mass $\sim 10^9$ $M_\odot$, which we call the massive core. The massive core a dynamical component lying in the center of a bulge. The bulge component follows with an exponentially decreasing SMD profile with a scale radius of about 0.5 kpc. The bulge is then surrounded by an exponential disk of a scale radius of a few kpc. In the figure we trace each component by a straight line.

The presently obtained mass distribution has been found to be common to almost all galaxies so far observed in our Virgo survey as well as in any nearby galaxies. The galactic mass distribution can be summarized to have a fundamental structure comprising a central black hole, massive core, bulge, disk, and a dark halo. This structure appears to be universal. The massive core of radii on the order of 100 pc may be a dynamical structure corresponding to the optical pseudo bulges as discussed in this issue (see Kormendy, this volume)

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. Besides the massive core, one of the interesting facts we noticed was highly concentrated

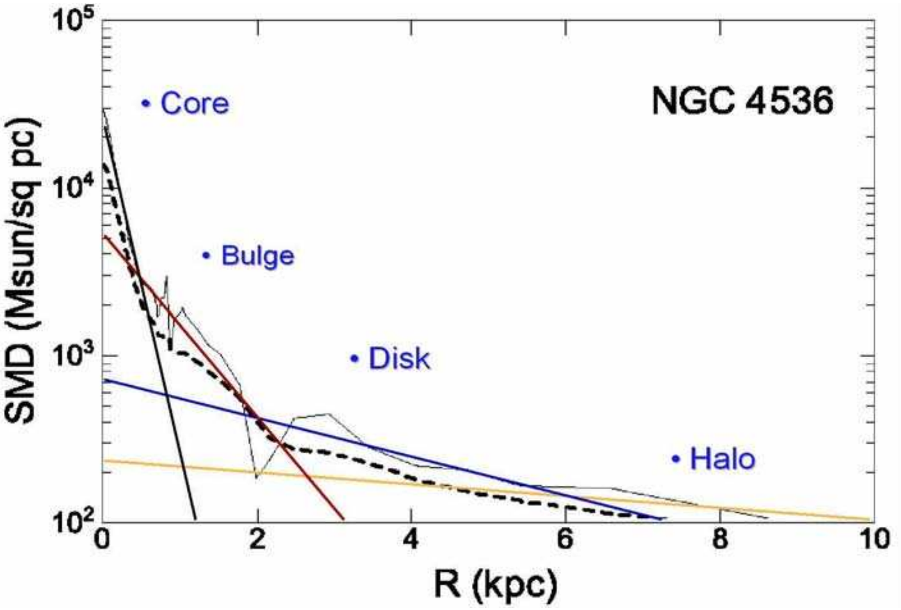

Figure 3. Surface mass density distribution in the nuclei of spiral galaxies, as observed for the spiral galaxy NGC 4536. Note the existence of a massive core of 100 pc radius with extremely high mass density.

molecular nuclei in several sample galaxies. Such high density molecular core was found for NGC 3079, which has been thought to be a peculiar and particular case for this galaxy (Sofue et al. 2001; Koda et al. 2007)

However, we have noticed that central high-density cores are not an exception, but are often found for the Virgo sample showing comparable gas density in the nuclei. We found five molecular nuclei, one semi-single peak, two twin peaks and/or ring type galaxies among our fifteen Virgo spirals. High-density molecular nuclei are also found for many galaxies by CO line surveys at various resolutions (Kenney et al. 1992, 1993; Sakamoto et al. 1999; Regan et a. 2001; Helfer et al. 2001; Schinnerer et al. 2002; García-Burillo et al. 2005).

In order to investigate the density distribution in and around the molecular nuclei, we used uniform weighting for UV plane of interferometer data analysis to obtain higher resolution maps ($\sim 1''$ resolution). Fig. 4 shows NGC 4536 from the Virgo sample, showing high-density molecular nucleus. In the figure we compare this galaxy with the typical molecular core in NGC 3079 at the same angular resolution ($\sim 1''$). They both show similar characteristics, both in the density and rotation. In our Virgo sample galaxies, we found more number of similar gas nuclei. Their central face-on column densities of molecular hydrogen were found to be as high as $N_{\rm H_2} \sim 10^{22} - 10^{23}$ $\rm H_2$ cm^{-2}. These values correspond to surface gas mass density $\Sigma_{\rm gas} \sim 10^2 - 10^3$ $\rm M_\odot$ pc^{-2}. Here, we assumed a conversion factor of 1.0×10^{20} $\rm H_2$ cm^{-2} K^{-1} km s^{-1}.

Fig. 5 the CO intensity of the molecular nuclei against dynamical surface mass density in the centers for several centrally peaked galaxies. Triangles denote plots for high resolution analysis with uniform weighting (resolution $\sim 1''$) and circles for natural weighting (resolution $\sim 4''$). The solid line indicates a gas

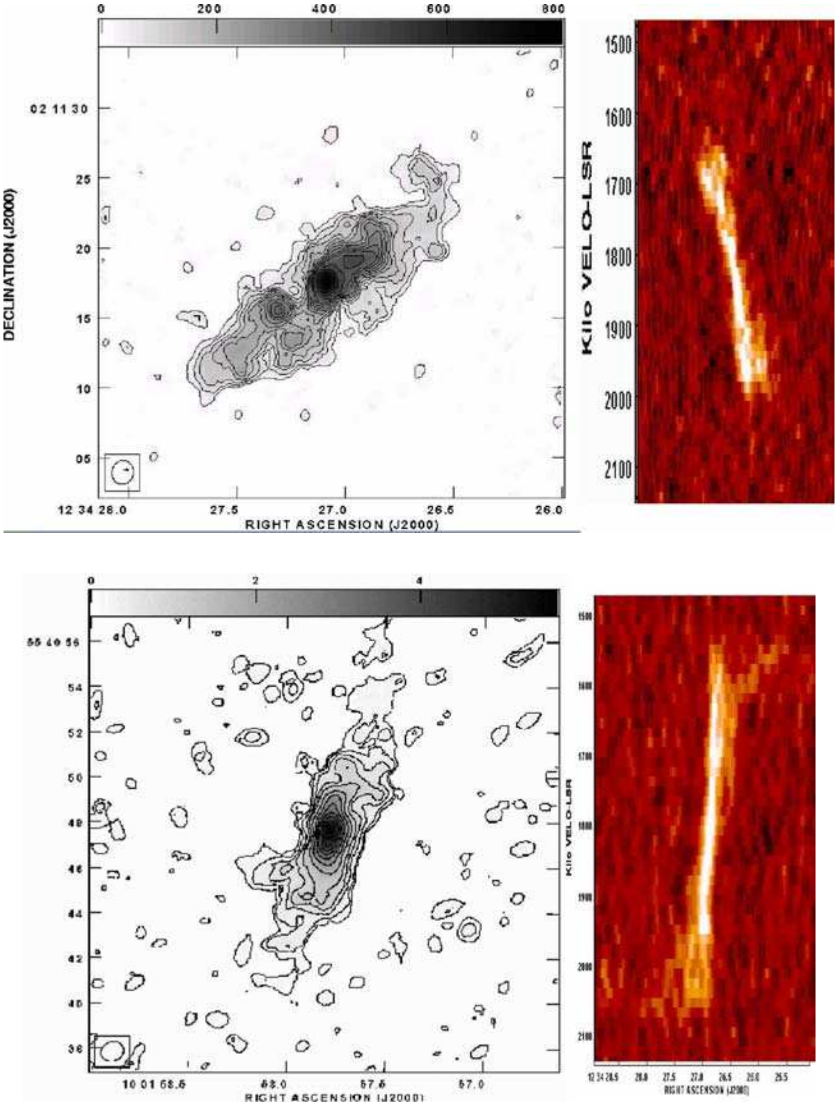

Figure 4. CO intensity distributions (left panels) and PV diagrams (right panels) for the molecular nuclei in NGC 4536 (top panels) and NGC 3079 (bottom panels) at high resolution $\sim 1''$

mass equal to 1.5% of the dynamical mass, which suggests that the dynamics of gas disk would be more controlled by strong gravitational force of the massive cores. The figure clearly shows that the central gas density in the molecular nuclei, once it is formed, is proportional to the dynamical surface mass density. The deeper is the gravitational potential in the center, the higher is the gaseous density.

The high column density of the molecular nuclei indicates a very high spatial gas density of $n \sim 10^3 - 10^4$ $\mathrm{H_2}$ $\mathrm{cm^{-3}}$, if the thickness is several tens of parsecs as in the case of the Milky Way center. The Toomre's Q value for these nuclei are calculated to be as large as $Q \sim 10$, which is mainly due to the high velocity

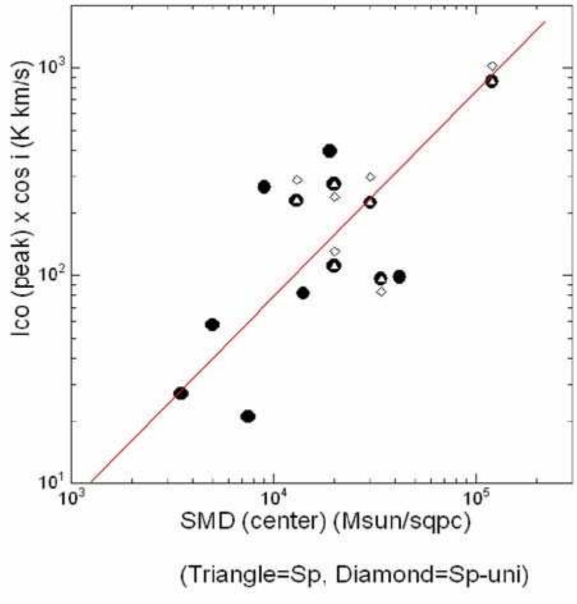

Figure 5. CO intensity plotted against the central SMD. Higher-mass cores nest higher-density molecular nuclei.

differential rotation in the massive cores. The Q-value stability in the central molecular disks has been discussed in relation to the pre-starburst accumulation of gas in the galactic centers (Kenney et al. 1992, 1993; Jogee et a. 2005). The high-density molecular nuclei in the Virgo sample may be an extreme case in such stable gaseous nuclei, and will be deeply related to the suppression and/or onsets of starburst in the central regions (Kennicutt 1998).

4. Summary

We have shown that central RCs of Virgo and nearby normal spiral galaxies show a steep rise in the central several tens of parsecs. The calculated mass distributions have the universal characteristics: the central black hole, massive core, bulge, disk, and dark halo. However, these components may not necessarily be distinguished from each other, but can be considered to be a continuous structure. The massive core may be dynamically corresponding to an optical pseudobulge (see Kormendy, this volume). The depth of the gravitational potential caused by the massive core is related to the density of accumulated gas density in the molecular nuclei: The deeper is the potential, the higher is the gas density. In some galaxies, the molecular nuclei exhibit extremely high gas density, as high as that of a giant molecular cloud. Although the density is high, the molecular gas appears to be gravitationally stable due to very-high differential rotation.

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