The Most Completely Sampled Rotation Curves for Galaxies

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Abstract

We have compiled high-resolution position-velocity diagrams observed along the major axes of nearby spiral galaxies in the CO-line emission, and derived rotation curves for the inner regions of the galaxies. We have combined the inner rotation curves with the outer HI and optical rotation curves to obtain the total rotation curves. The inner rotation curves are characterized by a steep increase within a few hundred pc radius, indicating a compact massive concentration near the nucleus. We fit the obtained rotation curves for individual galaxies by a modified Miyamoto-Nagai’s potential by assuming existence of four mass components; a nuclear mass component with a scale radius of 100-150 pc and a mass of \( \sim 3 - 5 \times 10^9 M_\odot \); a central bulge of 0.5 to 1 kpc radius of a mass \( \sim 10^{10} M_\odot \); a disk with scale radius 5 to 7 kpc and thickness 0.5 kpc of a mass \( \sim 1 - 2 \times 10^{11} M_\odot \); and a massive halo of scale radius 15 to 20 kpc with a mass \( \sim 2 - 3 \times 10^{11} M_\odot \). We discuss the implication of the nuclear compact mass component for the formation mechanism of multiple structures within the galactic bulge during its formation.


1. Introduction

The rotation curves of galaxies have been obtained by optical (H\(\alpha\)) and HI 21-cm line emission observations along the major axes (Rubin et al 1980, 1982). It is well known that the HI gas distribution generally shows depression in the central few kpc region (Bosma 1981; Rots et al 1990), which has yielded an apparently solid rotation curve for the central region. Optical measurements are affected by the contamination of the bright bulge light, which has also increased the uncertainty of the curve near the center. Moreover, because of the dust absorption in the gaseous disk, optical observations cannot be obtained of the central regions of highly-tilted galaxies, whereas edge-on galaxies are most suitable for determining the rotation curves without ambiguity of correction for inclination.

On the other hand, the CO-line emission is generally concentrated in the central region, so that rotation curves of the inner few kpc region can be most accurately obtained by CO position-velocity (PV) diagrams (Kenney & Young 1988; Young & Scoville 1992; Sofue & Nakai 1993; Sofue et al 1994). It has been shown that the CO rotation curves
of edge-on galaxies do not necessarily coincide with those obtained by HI and/or optical observations: The central rotation shown by CO is much flatter than that from HI and optical data, or even increases near to the center, exhibiting rapidly rotating compact disk component (Sofue et al 1988; Sofue and Nakai 1993, 1994; Sofue et al 1994).

In this paper, we compile CO-line PV diagrams along the major axes of nearby late type (Sb, Sc) galaxies observed with large-aperture telescopes and interferometers. Particularly, we extensively use CO-line data from the Nobeyama 45-m telescope with an angular resolutions 15″. We then deduce inner rotation curves from the CO PV diagrams, and combine them with outer HI and optical rotation curves, and obtain the most completely sampled rotation curves. Of course, this technique to deduce the inner rotation curve works when nuclear CO is present: significant quantities of nuclear CO might be not universal. We further fit the obtained curves with the Miyamoto potential (Miyamoto and Nagai 1975) by assuming four mass components: a nuclear compact mass, bulge, disk, and a massive halo.

2. CO + HI Position-Velocity Diagrams and Rotation Curves

2.1. Deriving Rotation Curves

2.1.1. Edge-on galaxies

Given a PV diagram along the major axis of an edge-on galaxy, the rotation curve can be derived by using the loci of terminal velocity ($V_t$) in the PV diagram. The terminal velocity is defined in a similar manner to that adopted for HI and CO-line PV diagrams for our Galaxy (e.g., Clemens 1985). Thereby, the velocity dispersion of the interstellar gas ($\sigma_{ISM}$) and the velocity resolution of observations ($\sigma_{obs}$) must be corrected by

$$V_{rot} = V_t - (\sigma_{obs}^2 + \sigma_{ISM}^2)^{1/2}.$$  

(1)

For the galaxies discussed in this paper, the velocity resolution was usually $\sigma_{obs} \sim 10$ km s$^{-1}$. We take the interstellar velocity dispersion same as that for molecular ISM in our Galaxy, $\sigma_{ISM} \sim 7$ km s$^{-1}$ (Stark and Brand 1989; Malhotra 1994). In this paper, we adopted a correction for the ISM velocity dispersion and velocity resolution as $V_{rot} \sim V_t - 12$ km s$^{-1}$. The accuracy of measuring the terminal velocity as below using PV diagrams was typically ±10 km s$^{-1}$. So, the accuracy of determination of rotation velocities is not largely dependent on the values of the velocity dispersion and resolution.

The terminal velocity is defined by a velocity at which the intensity becomes equal to

$$I_t = \left[ (0.2I_{max})^2 + I_{lc}^2 \right]^{1/2}$$

(2)

on observed PV diagrams, where $I_{max}$ and $I_{lc}$ are the maximum intensity and intensity corresponding to the lowest contour level, respectively. This equation defines a 20% level
of the intensity profile at a fixed position, \( I_t \simeq 0.2 \times I_{\text{max}} \), if the signal-to-noise ratio is sufficiently high. On the other hand, if the intensity is not strong enough, the equation gives \( I_t \simeq I_{\text{lc}} \) which approximately defines the loci along the lowest contour level (usually \( \sim 3 \times \text{rms noise} \)).

We comment that thus-traced rotation curves may not represent those corresponding to physically identical positions in galaxies, since different galaxies have different CO/HI intensities, and as well, their observational data are of different sensitivities and linear resolutions. A threshold column density instead of the above criterion might be a possible alternative. However, it is practically hard to apply it to different galaxies with different observational resolutions and sensitivities. Hence, the practical, and probably most reliable way to derive the rotation curves using radio PV diagrams is the method as described above. Obviously, the result is observation-limited (spatial and velocity resolutions and sensitivity), and depends on the proper line intensities of individual galaxies.

Fig. 1 shows an example of a composite PV diagram for NGC 891 reproduced from Sofue et al (1994). The CO gas is concentrated in the central region, while HI is distributed in the outer disk, having a void in the central region. In Fig. 1 we superpose the thus obtained rotation curve for NGC 891 as an example. The HI gas indicates the rotation of the outer disk, whereas the CO emission indicates the rotation in the innermost region including the rapidly rotating nuclear disk. The rotation curve as a function of the radius can be obtained by averaging and smoothing the absolute rotation velocities in both sides of the galaxy nucleus. The final rotation curves are then smoothed according to the angular resolution. The clumpy and smaller-scale structures, which are partly due to clumpy ISM distributions and molecular clouds and partly due to noise in the observations, are also smoothed by hand in drawing the final rotation curve.

In the following subsections, we derive rotation curves for individual galaxies. Generally, the rotation curves are almost flat even in the very inner region, much flatter than those obtained from HI or optical observations. We describe individual galaxies below, and summarize the observational parameters and references in Table 1.

2.1.2. Mildly tilted galaxies

For nearly face-on galaxies that have been observed with a sufficiently high angular resolution (e.g., sharper than a several tens pc), this method will give an almost identical rotation curve to that obtained by tracing intensity-weighted averages (e.g., using a velocity field map), which automatically account for the gas dispersion and velocity resolution. However, except for such an ideal case, both the finite beam and disk thickness along the line of sight cause confusion of gases with smaller velocities than the terminal velocity, and would result in a lower rotation velocity. Hence, even for galaxies with mildly-tilted galaxies observed with a finite beam width, we use PV diagrams along the major axes, and apply the same method as for edge-on galaxies.

2.1.3. Innermost Rotation Curves


This envelope-tracing technique has difficulty in applying to the innermost part of the PV diagram, since simply traced envelopes on the two sides of the nucleus have a discontinuity at the nucleus mainly due to the finite beam width. We have avoided this discontinuity by stopping the tracing at a radius corresponding to the telescope resolution, and then by connecting the both sides of rotation curve by a straight (solid-body like) line crossing the nucleus at zero velocity. Therefore, the resolution of an obtained rotation curve is limited by the angular resolution of the observation.

The inner rotation curves are determined by CO data, while those in the outer disk are determined from HI and optical data. When we used data from different observations, we adopted higher resolution data. The data are then smoothly connected by tracing higher-velocity parts. Note that CO data have usually higher resolution than HI. When comparable data were present in the same region, we simply averaged them.

2.2. Rotation Curves for Individual Galaxies

We present the thus obtained rotation curves for individual galaxies. Basic parameters such as the distance and references for individual galaxies are given in table 1.

2.2.1. NGC 253

For its proximity at a distance of 2.5 Mpc (Pence 1980), relatively low-resolution CO data obtained with the FCRAO 14-m telescope (Scoville et al 1985) could resolve the central molecular disk at a linear resolution of 45''=545 pc. A PV diagram obtained by Scoville et al (1985) indicates a steep increase of the rotation velocity near the nucleus within $R \sim 0.3$ kpc. An optical rotation curve has been obtained by Pence (1981), which indicates a flat rotation at 2 to 5 kpc radius. More outer rotation characteristics can be derived from an HI velocity field observed by Combes et al (1977).

By combining rotation curves derived from these diagrams, which are shown in Fig. 2a, we constructed a total rotation curve as shown in Fig. 2b, where the inclination of $i = 78.5^\circ$ has been corrected. Hereafter, figures a and b in each figure number will show fitted curves to data and the resultant rotation curve, respectively. The rotation velocity increases steeply in the central region, and attains a maximum velocity of 210 km s$^{-1}$ at $R \sim 0.3$ kpc. Then, the curve is almost perfectly flat until $R \sim 9$ kpc

2.2.2. IC 342

This is an almost face-on ($i = 25^\circ$) Sc galaxy at 3.9 Mpc distance. It has been extensively studied in the CO line, and various PV diagrams have been obtained (Young and Scoville 1982; Hayashi et al 1987; Sage and Solomon 1991). Rotation curve in the HI line has been obtained by Rogstad and Shostak (1972). We here make use of PV diagrams observed with the Nobeyama 45-m telescope at a resolution of 15'' (284 pc; Hayashi et al 1987) and a 4''-resolution mm-Array PV diagram (Ishizuki et al 1990a; Ishizuki, private
communication). Fig. 3 shows the obtained rotation curve for IC 342 using the PV diagrams.

The rotation velocity increases almost rigidly in the innermost region at \( R < 10'' = 190 \text{pc} \), and reaches \( V_{\text{rot}} \sim 130 \text{ km s}^{-1} \) at \( R \sim 15''(280) \text{pc} \). Then, it increases gradually to reach a maximum velocity at \( 190 \text{ km s}^{-1} \) at \( R \sim 2 - 3' \ (2-3 \text{kpc}) \), followed by a flat HI rotation at 195 (at 8 kpc) to 190 km s\(^{-1}\) (at 20 kpc).

2.2.3. NGC 891

This edge-on Sb galaxy at a distance of 8.9 Mpc has been extensively observed in the CO line using the IRAM 30-m telescope (Garcia-Burillo et al 1992), NRO 45-m (Sofue and Nakai 1993), and OVRO interferometer (Scoville et al 1993). curve. It has been mapped in the HI line (Sancisi 1976a; Rupen 1991) at a comparable resolution to the CO observations. In Fig. 1 we show a composite PV diagram of the CO and HI lines reproduced from Sofue et al (1994). The CO diagram is characterized by the 4-kpc molecular ring and the high-velocity nuclear disk at \( R < 1 \text{kpc} \). The HI gas is distributed in a broad ring and outskirts at \( R > 10 \text{kpc} \). For deriving the rotation curve near the nucleus, we also made use of the IRAM CO\((J = 2 - 1)\) observation at a 13'' resolution (Garcia-Burillo et al 1992) and the higher resolution PV diagram obtained by interferometer observations by Scoville et al (1993).

The obtained rotation curve is given in Fig. 4. After a steep rising up near the nucleus, the rotation velocity attains a steep maximum over 250 km s\(^{-1}\), followed by a dip at \( R = 2 \text{kpc} \). Then, it becomes almost flat at \( R \sim 3 \text{kpc} \), and remains so until \( R \sim 15 \text{kpc} \). Beyond this radius, the rotation velocity gradually declines toward the outermost region. The rotation curve is very similar to that of our Galaxy (Fig. 11).

2.2.4. NGC 1808

NGC 1808 is an Sbc galaxy known for its dusty jet (Véron-Cetty and Véron (1985), and the distance is 11.4 Mpc for a Hubble constant of 75 km s\(^{-1}\)Mpc\(^{-1}\), and the inclination angle is \( i = 58^\circ \). HI observations using the VLA (Saikia et al. 1990) indicated a circular rotation ring of about 7 kpc radius. Koribalski et al. (1993) performed a mapping of the HI-line absorption in the nuclear region using the VLA, and found a nuclear ring of cold, dense rotating gas disk of radius 500 pc. Dahlem et al (1990) used the SEST 15-m telescope to map NGC 1808 in the CO line emission at an angular resolution of 43'', revealing a central condensation of molecular gas. We have mapped the central 1' region using the Nobeyama 45-m telescope at a resolution of 15'' in the CO emission, and obtained a high-resolution PV diagram along the major axis (Sofue et al: private communication). This diagram shows a high-velocity rotating nuclear disk, consistent with the result of Koribalski et al (1993). These PV diagrams have been used to construct a rotation curve as shown in Fig. 5. The rotation speed increases steeply to 210 km s\(^{-1}\) at \( R \sim 10'' \ (500\text{pc}) \).
pc) in the nuclear region, and then decreases to 190 km s\(^{-1}\) at \(R \sim 3\) kpc. It increases again to a maximum of 210 km s\(^{-1}\) at \(R \sim 2'\) (7 kpc) in the HI rotation curve. Beyond this radius, the rotation declines to \(V_{\text{rot}} \sim 130\) km s\(^{-1}\) at \(R \sim 6'\) (18 kpc). Such a declining rotation in the outskirts is rather exceptional among the galaxies studied here except M51 outskirts, suggesting a small-mass massive halo.

2.2.5. NGC 3079

This is an amorphous edge-on galaxy classified as Sc type, showing an anomalously high concentration of CO gas in the center (Sofue et al 1994). The distance is taken to be 15.6 Mpc according for the galacto-centric HI systemic velocity and a Hubble constant of \(H_0 = 75\) km s\(^{-1}\)Mpc\(^{-1}\) (Sofue and Irwin 1992). Fig. 6 shows the rotation curve produced by using the composite CO + HI PV diagram obtained by Sofue et al (1994). Here, they used a VLA HI PV diagram from Irwin and Seaquist (1991) and CO data from the Nobeyama mm Array (Sofue and Irwin 1992). This galaxy exhibits an exceptionally high concentration of CO emission in the galactic center. This high-density nuclear disk is clearly visible as the absorption feature in the HI line.

The rotation velocity shows a steep rising-up to a maximum as high as 320 km s\(^{-1}\) in the SE side and 260 km s\(^{-1}\) in the NW, followed by a dip at a few kpc radius. The rotation velocity of this nuclear disk component is highly asymmetric with respect to the nucleus. The asymmetric rotation continues until \(r \sim 8\) kpc. The HI gas is widely distributed in the broad ring at \(R = 1' - 2'\) (5 - 10 kpc) and in the outskirts showing a symmetric flat rotation.

2.2.6. NGC 4565

This is an almost edge-on (\(i \approx 86^\circ\)) Sb galaxy at a distance of 10.2 Mpc. A CO + HI composite PV diagram similar to Fig. 1 has been obtained by Sofue et al (1994) who used CO data from Nobeyama (Sofue and Nakai 1994) and HI from the VLA (Rupen 1991). The CO PV diagram shows a significant asymmetry in the intensity distribution: the CO emission in the SE few kpc region is very weak, so that the CO rotation in this is region is not clear. However, except for this region, the total rotation characteristics is almost symmetric, and mimics that of NGC 891. On the other hand, the HI diagram shows an almost perfect symmetry both in intensity and rotation velocity.

The rotation curve as obtained from these diagrams is shown in Fig. 7, which is similar to that for NGC 891. It has a nuclear-disk component rotating at 260 km s\(^{-1}\), followed by a flat rotation until 20-25 kpc at velocity as high as \(\sim 250\) km s\(^{-1}\). This galaxy is one of those with extremely flat rotation even in the outskirts, suggesting a large extended massive halo.
This nearly face-on Sbc galaxy at an inclination 20° and distance 9.6 Mpc has been extensively studied in all wavelengths. Tully (1974) derived a rotation curve from their optical spectroscopic data for a wide area. Rots et al (1990) have extensively mapped this galaxy in HI, and obtained an intensity-averaged HI velocity field. However, they are not appropriate to derive an inner (a few kpc) rotation curve, because the HI emission is very weak in the central region (Rots 1990), so that the intensity-averaged velocity is significantly weighted by rotation velocity at larger radius. Unfortunately, no HI PV diagram has been obtained as yet along the major axis. A high-resolution CO PV diagram has been obtained by Garcia-Burillo et al (1993) and by Nakai et al (1995 in preparation). We here use the CO PV diagram by Garcia-Burillo et al. The outer rotation curve can be also obtained by the HI velocity field, which agrees with that obtained from the CO data.

After correcting for the inclination of $i = 20°$, we obtained CO and Hα rotation curves as shown in Fig. 8a. The CO rotation velocity at $R < 5$ kpc is significantly higher than that from the Hα velocity. This may be due to the fact that the density wave velocity jump in the arms of M51 is as high as $\sim 50$ km s$^{-1}$, which would cause a systematic velocity difference of CO emitting regions (dark lanes) from star forming regions (OB stellar arms) (Nakai et al in preparation). According to the definition of a rotation curve, we here simply adopt the highest velocities (terminal velocities) along the major axis. Hence, most part of the final rotation curve obtained in Fig. 8b coincides with the CO rotation curve. The rotation velocity increases steeply near the nucleus within 0.5 kpc, reaching a maximum of 260 km s$^{-1}$. Then, it remains flat up to 9 kpc, beyond which the rotation velocity declines to 130 km s$^{-1}$ at $R \sim 15$ kpc. This declining rotation is similar to that observed in NGC 1808.

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2.2.8. NGC 5907

NGC 5907 is a nearby Sc galaxy with an almost edge-on orientation at an inclination angle of 88°. Observations of the HI line emission have shown a large disk of interstellar gas, which is warping in the outermost regions (Sancisi 1976b). A CO + HI composite PV diagram for NGC 5907 has been obtained by Sofue et al (1994), who used CO data from Nobeyama (Sofue 1994) and HI data from the WSRT (Casertano 1983). Recently, a nuclear disk component has been observed in the in CO ($J = 2 - 1$) line with the IRAM 30-m telescope, which showed two symmetrical humps in the PV diagram at rotation velocities $+200$ and $-190$ km s$^{-1}$ at 10′′ to the NW and SE of the nucleus. This indicates that the rotation velocity increases steeply in the central $\sim 10''$ (500 pc). Unfortunately, the HI PV diagram has been obtained only for the SE side, which we used to derive an HI total rotation curve, assuming that the rotation is axisymmetric. So, we first obtained CO rotation curve at $R < 10$ kpc by averaging the SE and NW CO curves, and obtained final rotation curve in Fig. 9b by smoothing the CO and HI total rotation curves. After the steep rising near the nucleus, the rotation curve is almost flat until 20 kpc, beyond which it is gradually declining.
2.2.9. NGC 6946

This is an nearly face-on galaxy at a 5.5 Mpc distance, and has been observed in high resolution in the CO line (Sofue et al 1988; Ishizuki et al 1990b; Casoli et al 1990). Ishizuki et al (1990b) have obtained a CO PV diagram using the Nobeyama mm Array at a resolution of $4''$, which showed a very steep rising of the rotation velocity up to a sharp maximum at 220 to 230 km s$^{-1}$ within the central $2''$ (53 pc). An inner rotation curve obtained from this PV diagram is shown in Fig. 10a-1. Sofue et al (1988) have obtained a wide-area rotation curve by combining CO data from the NRO 45-m observations with an HI rotation curve by Tacconi and Young (1986). They have shown that the rotation is almost perfectly flat from the very center to the outskirts at $R \sim 15$ kpc. Casoli et al (1990) have combined the CO PV diagram from IRAM 30-m observations with an HI PV diagram, showing that the rotation is almost flat toward the center. We used this PV diagram to obtain a CO rotation curve shown in Fig. 10a-2.

We have combined all these rotation curves in Fig. a-1 and a-2, and obtained a rotation curve as shown in Fig. 10a-3 and 10b. Here we have corrected for the inclination of $i = 30^\circ$. The steep rising near the nucleus is followed by a decrease to a dip at about 1 kpc, followed by a flat minimum at 185 km s$^{-1}$ until 3 kpc. Then, the rotation velocity gradually increases to attain 220 km s$^{-1}$ at $R \sim 7$ kpc, beyond which the rotation is nearly flat. The flat rotation appears to continue until the observed edge of the galaxy at $R \sim 16$ kpc. The rotation curve mimics the one for our Galaxy as shown in the next subsection.

2.3. The Milky Way

The Milky Way Galaxy has long been observed both in HI and CO, and many longitude-velocity ($l - V_{lsr}$) diagrams have been published. These diagrams have been used to obtain rotation curves of the Galaxy: Burton and Gordon (1978) obtained an HI rotation curve at a $0''$.5 resolution for the galactic disk within the solar circle, and combined the HI data with CO data at $l > 8^\circ$. Clemens (1985) have analyzed the $^{12}$CO line survey data for $l > 13^\circ$, and integrated all the existence rotation curves to present a total rotation curve of the Galaxy including the outer disk of the solar circle. In these studies, the rotation of the central few degree region has been obtained by the terminal-velocity tracing method of the HI data (Burton and Gordon 1978). In Fig. 11 we reproduce the total rotation curve derived by Clemens et al (1985). Here, the solar rotation and radius are taken to be 220 km s$^{-1}$ and 8.5 kpc, respectively.

2.4. Comparison of Rotation Curves
All the rotation curves obtained in this work are shown in the same scale in Fig. 12a and b. Fig. 12a shows the rotation curves with a steep central peak, while Fig. 12b shows those without. Generally, the rotation velocity rises steeply within a few hundred pc, indicating the existence of a central compact mass component. Many galaxies (the Milky Way, NGC 891, NGC 3079, NGC 6946) exhibit a sharp maximum at $R \sim$ a few hundred pc, reaching a velocity as high as $\sim 200$ to $300 \text{ km s}^{-1}$. On the other hand, the maximum velocity corresponding to this component is not so high in such galaxies as NGC 253, IC 342, and M51, where the existence of the steep and sharp rising near the nucleus is also evident.

3. Fitting by Miyamoto-Nagai Potential

We try to fit the rotation curves by the Miyamoto-Nagai (MN) (1975) potential. The modified Miyamoto and Nagai’s (1975) potential with $n$ mass components is expressed in a $(R, z)$ coordinate as the following. Here, $R$ denotes the distance from the rotation axis and $z$ is the height from the galactic plane.

$$
\Phi = \sum_{i=1}^{n} \frac{GM_i}{\sqrt{R^2 + \left(a_i + \sqrt{z^2 + b_i^2}\right)^2}},
$$

where $M_i$, $a_i$ and $b_i$ are the mass, scale radius, and scale thickness of the i-th mass component of the galaxy. For a spherical mass distribution, we have $a_i = 0$, and $b_i$ becomes equal to the scale radius of the sphere. The rotation velocity is calculated by

$$
V_{\text{rot}} = \left(R \frac{\partial \Phi}{\partial R}\right)^{1/2}.
$$

Miyamoto and Nagai (1975) have assumed two components ($n = 2$). In order to fit the flat rotation at $R \sim 10 - 20 \text{ kpc}$, an extended massive halo has to be introduced. Since their model has been proposed, a three-component model ($n = 3$) has been widely used, which assumes the central bulge, disk, and massive halo. However, after a trial of fitting to the rotation curves of the central few hundred pc region as obtained here, it turned out that the usual three-component model is not sufficient to fit the steep central peak. We have, therefore, introduced a fourth component which represents a more compact nuclear component in addition to the usual three components.

Fig. 13 shows an example of a calculated rotation curve of this “four-component” model ($n = 4$), where we assumed (1) a nuclear compact mass component, (2) bulge, (3) disk, and (4) a massive halo. The table inset in the figure presents the parameter combination. Dashed lines indicate rotation curves corresponding to individual component. The rotation curve of our Galaxy, except for the central 10-50 pc, can be fitted by a model
with (1) a nuclear mass of $M_1 = 5 \times 10^9 M_\odot$ of a $b_1 = 120$ pc scale radius; (2) the bulge of $M_2 = 10^{10} M_\odot$ and $b_2 = 750$ pc radius; (3) the disk of $M_3 = 1.6 \times 10^{11} M_\odot$ with radius $a_3 = 6$ kpc and thickness $b_3 = 0.5$ kpc; and (4) a massive halo of $M_4 = 3 \times 10^{11} M_\odot$ and scale radius of $a_4 = b_4 = 15$ kpc. The rotation of NGC 891 can be reproduced by the same model with a similar parameter combination.

In this four-component model, however, the very inner rotation within a few tens of pc region of the Galaxy, as shown in Fig. 11a-3, cannot be reproduced. Since it is beyond the scope of the present paper to discuss a detailed nuclear mass distribution, we only argue for the necessity of introducing more central components. In order to fit the observed inner rotation curve, we need to add a fifth component at the nucleus with a smaller scale ($\sim 30$ pc radius and mass ($\sim 10^7 M_\odot$), and, as well, a central point-like mass of a few $10^6 M_\odot$.

Similarly, the rotation curve observed for NGC 6946 is fitted by the model as shown in Fig. 14. The flat valley at $R \sim 1$ to 2 kpc region can be fitted well by introducing the four-component model, which was difficult to reproduce by the three-component model. The rotation of NGC 3079 can be fitted by a similar model. The rotation curves of NGC 253 and IC 342 can be fitted by the same model with a smaller-mass nuclear component, as shown in Fig. 15 and 16. Rotation curves for the other galaxies can be also reproduced by this model assuming parameters in between Fig. 13 to 16.

In the above fitting to the Miyamoto-Nagai potential with the four mass components, we chose the parameters by trial and error. Even through such a fitting, the parameters (mass and scale radii) can be constrained within an error of about 10 to 20%, depending on the quality and resolution of the data. A detailed least-squares fitting to the data would provide us of more realistic sets of parameters.

We have so far called the obtained diagrams the “rotation curves”. However, they actually meant observed loci of the highest velocity envelopes in the position-velocity diagrams. However, non-circular motion such as due to a barred potential and density waves would be superposed on the actual motion of gas, particularly in the central regions. We, therefore, estimate the deviation of the tangential velocity represented by the observed PV diagrams along the major axis from that of a circular rotation. Suppose that gas clouds are orbiting on elliptical orbits of eccentricity $e$. Then, the orbital velocity of a cloud at the perigalactic passage is given by

$$V_0 = V_{\text{rot}} \sqrt{1 + e},$$

where $V_{\text{rot}}$ is the circular velocity corresponding to the mass distribution as calculated by eq. (4). The loci of maximum velocity on the PV diagram will approximate this perigalactic (maximum) orbital velocity.

Therefore, the “rotation curve” may indicate a slightly over-estimated circular velocity by a factor of $\sqrt{1 + e}$. For a highly disturbed orbits of gas in a strong bar shock as numerical simulations have shown (Fujimoto et al 1977; Huntley et al 1978; Noguchi 1988; Wada and Habe 1992), the eccentricity is found to be of the order of $e \sim 0.5$ Hence, the apparent
rotation velocity from the PV diagrams would be only $\sim 20\%$ higher than a purely circular velocity even in such an extreme barred-shocked condition. This would, however, result in an overestimation of the mass component by a factor of $1 + e$, causing an overestimation of a few tens of percent. Finally, we mention that the rotation of the major gas disk in the central 150 pc of our Galaxy has been shown to be almost circular from a detailed analysis of the CO PV diagrams of Bally et al (1987) (Sofue 1995).

4. Discussion

We have compiled position-velocity (PV) diagrams along the major axes of nearby galaxies, which have been observed in the CO line (central regions), H$\alpha$ emission (star forming disk), and in HI lines (disk and outskirts). We used these PV diagrams to obtain total rotation curves from the nuclear region to outskirts. The obtained total rotation curves are shown to be approximately flat from the nuclear region of a few hundred pc radius to outer $R \sim 10 - 30$ kpc region, except for the inner few hundred pc.

A striking feature obtained in the present study is the steeply rising nuclear peak of the rotation curves at $R \sim 100$ to 200 pc, which is generally observed for all the disk galaxies studied here. This steep rotation peak can be fitted by a mass model in which a compact nuclear mass component of a 100 to 150 pc radius and a mass of several $10^9 M_\odot$ is assumed. From a fitting of the observed rotation curves by the Miyamoto-Nagai (1975) potential, this nuclear mass component has turned out to be an additional component to the well known central bulge: The rotation curves of galaxies can be thus generally fitted by a model with four mass components: the nuclear compact mass, central bulge, disk, and the massive halo.

The nuclear mass component would have an essential implication for the formation and evolution of the galactic bulge and the central mass condensation of galaxies. Saio and Yoshii (1990) have shown that the flat rotation curve and exponential-raw mass distribution in disk galaxies are a consequence of a viscous protogalactic disk contraction with on-going star formation, where the time scales of viscosity and star formation are of the same order, or of the order of the Jeans time of the disk instability. Their model has also produced a central enhancement of the rotation velocity at $R \sim 0.05R_0$ with $R_0$ being the scale radius of the disk. This is due to a more rapid contraction of the central gas disk compared to the star formation time because of a stronger shearing-viscosity in the central disk. The model rotation curves could somehow mimic even the central velocity peak of the observed curves such as in the Milky Way, NGC 891 and NGC 6946.

However, the model appears to be still not satisfactory in reproducing in detail the steep central peak of rotation curves at $R < \sim 200$ pc corresponding to the compact nuclear mass component. In order for such a compact mass component to appear, a much more rapid contraction of protogalactic gas disk would have been necessary. Such a rapid contraction of gas disk prior to star formation may be possible if we could modify (increase) the viscosity in the central gas disk. Alternatively, we may need to take into account a rapid gas accretion through strong galactic shocks in a central oval (bar) potential (Noguchi 1988; Wada and Habe 1992) during the proto-galactic disk contraction.
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Figure Captions

Fig. 1: CO + HI composite position-velocity diagram for NGC 891 as reproduced from Sofue et al (1994). A rotation curve is superposed by the thick line.

Fig. 2: (a-1) Inner rotation curve of NGC 253 derived by using the CO PV diagram. (a-2) CO + optical (Hα) (= total) rotation curve compared to HI rotation. (b) Total rotation curve of NGC 253 by averaging and smoothing the eastern and western half of the rotation velocities. See Table 1 for observational parameters and references.

Fig. 3: (a-1) CO rotation curves for IC 342 obtained by NRO 45-m telescope and the mm-wave array. (a-2) CO rotation curves obtained by lower resolution observations compared to those in (a). (a-3) CO rotation curve obtained using curves in (a) and (b). (b) Total rotation curve of IC 342 obtained by combining and smoothing the CO curves with HI curve.

Fig. 4: (a) CO and HI rotation curves for NGC 891 shown separately for the NE and SW part along the major axis. (b) Total rotation curve of NGC 891.

Fig. 5: (a) CO and HI rotation curves for NGC 1808. (b) Total rotation curve.

Fig. 6: (a) CO and HI absorption rotation curves for the inner region combined with the HI rotation for the outer part. (b) Total rotation curve for NGC 3079.

Fig. 7: (a) Inner CO and outer HI rotation curves for NGC 4565. (b) Total rotation curve.

Fig. 8: (a) CO and optical rotation curves for NGC 5194 (M51). (b) Total rotation curve of M51.

Fig. 9: (a) CO + HI rotation curves for NGC 5907. (b) Total rotation curve.

Fig. 10: (a-1) CO rotation curve from the mm-array for the nuclear region of NGC 6946. (a-2) CO rotation curves. (a-3) CO + HI rotation curves. (b) Total rotation curve of NGC 6946.

Fig. 11: Rotation curve of the Galaxy reproduced from Clemens (1985).

Fig. 12: Rotation curves of galaxies studied in this paper plotted in the same linear and velocity scales.

(a) Rotation curves having a central peak similar to that of our Galaxy.
(b) Rotation curves without significant central peak.

Fig. 13: A model rotation curve of our Galaxy as calculated for the Miyamoto-Nagai (1975) potential with four components: (1) Nuclear mass component; (2) Bulge component with scale radius a few hundred pc; (3) Disk component; and (4) Massive halo component. The mass $M$ in $10^{11} M_\odot$, scale radius $a$ and the thickness $b$ in kpc of each component are indicated by the inset table. The inset table shows the mass $M$ in $10^{11} M_\odot$, scale radius $a$ and thickness $b$ in kpc for the four mass components of the modified Miyamoto-Nagai potential in equation (3). Dashed lines indicates rotation velocities corresponding to each mass component.

Fig. 14: The same as Fig. 13, but mimicking that of NGC 6946.

Fig. 15: The same as Fig. 13, but mimicking that of NGC 253 with a smaller-mass nuclear component.

Fig. 16: The same as Fig. 13, but mimicking that of IC 342.