CO vs HI ROTATIONS OF GALAXIES

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Abstract

Since molecular gas is distributed in the inner disk of galaxies while HI in the outer disk, CO emission can trace the inner rotation curves more accurately than HI. We have derived most-completely sampled rotation curves by combining HI and CO position-velocity diagrams. We show that inner rotation curves have a steep increase within the central few hundred-pc region. The inner behavior of rotation can be fitted by the Miyamoto-Nagai potential, only if a central mass component with scale radius of $100 - 200$ pc and a mass of $\sim 3 - 5 \times 10^9 M_\odot$ is assumed in addition to the usual bulge. This implies that the central $\sim$ 100-pc region has a stellar mass density as high as several hundred $M_\odot$pc^{-3}, orders-of-magnitudes higher than that for a single bulge and disk (several $M_\odot$pc^{-3}). Such a concentric multi-component structure within a bulge ("bulge in bulge") may have crucial implication for the dynamical evolution of the central regions of galaxies. Since the molecular gas distribution is closely correlated with optical disk, CO line can be used for the line width-luminosity (Tully Fisher) relation in addition to (instead of) the HI line. We show that the CO-line width-luminosity relation can be a powerful routine method to derive distances of cosmologically-remote galaxies and the Hubble parameter for a significantly large volume of the universe. By applying the CO-line width-luminosity relation to CO-line data by large-aperture mm-wave telescope, we have derived distances to galaxies at $cz \sim 20,000$. In order to measure the inclination and magnitudes, we performed optical imaging observations of thus CO-detected galaxies using the CFHT 3.6-m telescope at high resolution. The radio and optical data have been combined to derive the distances to the galaxies. We further derived the Hubble ratio for these galaxies by applying the CO-line width-luminosity relation. [1]

Key words Galaxies: kinematics – Galaxies: rotation – Galaxies: distances – Galaxies: ISM

1 Inner CO vs Outer HI Rotation Curves

1.1 Most-Completely Sampled Rotation Curves

Rotation curves (RC) are the principal tool to derive the distribution of mass in galaxies, and have been investigated extensively based on optical (Hα) and HI-line observations along

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the major axes of galaxies (Rubin et al 1980, 1982; Persic et al 1995) and the Galactic plane (Burton and Gordon 1978; Clemens 1985). Recently, we obtained most-completely-sampled rotation curves for many nearby galaxies by combining high-resolution CO and HI position-velocity diagrams with a particular concern with central behavior of RC (Sofue 1996a). It was shown that RC for galaxies in this study rises very steeply within 100 – 200 pc region of the center (Fig. 1). Among them, the inner RC of NGC 891, NGC 3079, and NGC 6946 were shown to have a sharp central peak, very similar to that observed for the Milky Way. Such a steep rising has been not well detected in the current optical and HI RC analyses.

We show that the innermost RC can be well reproduced by a mass model in which a fourth mass component is present within the central bulge in addition to the usual bulge, disk and massive halo (Sofue 1996b). We discuss the implication of the four-mass component model and a "bulge-in-bulge" structure for the dynamical evolution of the central region of galaxies.

1.2 Fitting by Four-Mass Component Potential: Bulge in Bulge

We try to fit the RC by the Miyamoto-Nagai (MN) (1975) potential, which is most suitable to represent an axisymmetric mass distribution comprising multiple components satisfying the Poisson's equation. The MN potential with n mass components is expressed as

$$\Phi = \sum_{i=1}^{n} GM_i[R^2 + \{a_i + (z^2 + b_i^2)^{1/2}\}^2]^{-1/2},$$

Here, R denotes the distance from the rotation axis, z is the height from the galactic plane, and M_i, a_i and b_i are the mass, scale radius, and scale thickness, respectively, of the i-th mass component. For a spherical mass distribution such as for a bulge, we have $a_i = 0$, and b_i becomes equal to the scale radius of the sphere. The rotation velocity is calculated by

$$V_{\rm rot} = (R\partial\Phi/\partial R)^{1/2}\,.$$

Miyamoto and Nagai (1975) have assumed two components ($n = 2$) in order to describe the bulge + disk structure of the Galaxy. In order to fit the flat rotation at $R \sim 10 - 20$ kpc, an extended massive halo has to be introduced, and a three-component model ($n = 3$) is widely used, assuming a bulge, disk, and massive halo.

After a trial of fitting to the RC of the central few hundred pc region, it turned out that the usual three-component model is not sufficient to fit the steep central peak. It is necessary to introduce a fourth component which represents a more compact component in addition to the usual bulge.

In the first panel of Fig. 1 we show a RC of the Galaxy calculated by this four-component model (thin full line), and the observed RC from Clemens (1985) is superposed by a thick line. Dashed lines indicate RC corresponding to individual components. The observed RC is fitted well by a model with: (1) A massive halo of $M_1 = 5 \times 10^{11} M_{\odot}$ and scale radius of $a_1 = b_1 = 15$ kpc in order to fit the flat part of the RC in the outer Galaxy; (2) A disk of $M_2 = 1.5 \times 10^{11} M_{\odot}$ with scale radius of $a_2 = 6$ kpc and thickness $b_2 = 0.5$ kpc. Hereafter, we fix $b_2 = 0.5$ kpc for all galaxies, since RC is not sensitive to b_2 if $a_2 >> b_2$. (3) A spherical ($a_3 = 0$) bulge of $M_3 = 1.5 \times 10^{10} M_{\odot}$ and $b_3 = 0.9$ kpc radius; and (4) A spherical ($a_4 = 0$) central component of $M_4 = 5.5 \times 10^9 M_{\odot}$ of a $b_4 = 150$ pc scale radius. We stress that this central component is more extended than the circum-nuclear mass condensation within $R \sim$ 50-pc, where the stellar density increases toward the nucleus roughly obeying a power law (Genzel and Townes 1987). In order to reproduce this innermost mass distribution, a fifth or more additional components with smaller scale radii would be required.

The RC for the other nine galaxies are also fitted by this model. Fig. 1 shows thus-calculated RC compared with the observations. Generally, all the RC are well reproduced by the model. Particularly, the sharp central peaks observed for the Galaxy, NGC 891, NGC 3079 and NGC 6946 are well fitted by the 4-th component with similar parameters. Flat valleys of RC at $R \sim 1$ to 2 kpc observed for NGC 6946 and NGC 3079 are also well reproduced by the present model, which are difficult to fit by any three-component model. Galaxies like NGC 253 and IC 342 have no sharp peak of RC, but show a steep rising up near the center followed by a sudden turn-off to a flat RC. This behavior can be well reproduced by the existence of the 4-th component. Only one case, the outer decline of RC of M51, was difficult to fit with the present model: The RC declines suddenly beyond $R = \sim 9$ kpc, whereas it is almost flat inside. Such a sudden decline of RC cannot be fitted by any simple gravitational potential even without the halo component, and might be due to some non-circular motion induced by the tidal interaction with the close companion. Table 1 summarizes the best-fit parameters for the observed galaxies. Errors of fitted parameters for the inner three components ($i = 2, 3, 4$) are within $\pm 15\%$ as eye-estimated during trials of fitting. Errors for the halo components are $\sim \pm 25\%$ for galaxies with RC observed at 15 to 20 kpc, while errors are larger, $\sim 50\%$, for galaxies with RC available only at $R < 10 - 15$kpc like NGC 253.

The density corresponding to the potential is given by $\rho = (1/4\pi G)\Delta\Phi$. The central density for each component ρ_i^0 can be calculated for $(R, z) = (0, 0)$, and we list the values in Table 1. The 4-th component has a mass density at the center as high as $\rho_4^0 \sim 10^2 - 10^3 M_{\odot}$ pc^{-3}, orders of magnitudes higher than that estimated from a single-bulge + disk model ($\rho_3^0 \sim 10 M_{\odot}$ pc^{-3}). The density of a spherical component varies with radius r as $\rho = \rho_i^0[(r/b_i)^2 + 1]^{-2.5}$ with $\rho_i^0 = (3M/4\pi)b_i^{-3}$. The surface density of the spherical component as projected on the sky varies as $\sigma_i(r) \simeq \sigma_i^0[(r/b_i)^2 + 1]^{-2}$ with $\sigma_i^0 = M/\pi b_i^2$. We emphasize that the high central density due to the 4th component superposed on the 3rd component cannot be obtained by an $e^{-(r/b_i)^{1/4}}$ law for a single bulge.

1.3 Implication for Dynamics in the Central Regions

1.3.1 Effect of a Bar

The "rotation curves" are obtained as loci of the highest-velocity envelopes in position-velocity plots along the major axes of galaxies. Therefore, non-circular motion due to a bar or oval potential would be superposed on the circular motion. If bar-shocked gas dominates in the CO emission, and if the bar axis is perpendicular to the line of sight, the radial velocity will be almost equal to the pattern speed of bar in rigid rotation, much smaller than the circular velocity (e.g., Sϕrensen et al 1976). On the other hand, if the bar is parallel to the line of sight, the velocity will be even larger than circular speed. The fact that all galaxies studied here show a steep rise-up near the center should be taken as an indirect evidence for a weak (or no) bar-shock, because the probability of looking at a bar parallel is small. We also mention that the CO gas in the central 150 pc of our Galaxy is nearly in circular rotation, and non-circular motion is at most ~ 40 km s^{-1}(Sofue 1995). Velocity fields observed for the central regions of NGC 6946 and IC 342, known for a bar of molecular-gas in the center (e.g., Ishizuki et al. 1990), also indicate that non-circular velocities are $\sim \pm 40$ km s^{-1}.

Weak-bar approximation within the central few hundred parsecs would be reasonable also from another point of view: According to the present analysis, the potential in the central a few hundred-pc region is dominated by the spherical condensation of mass, whose density and total mass are orders of magnitudes greater than the density and mass due to the disk component. Therefore, even if a bar instability is induced in the disk, it may be easily stabilized

Figure 1: Model RC of galaxies as calculated for a Miyamoto-Nagai potential with four mass components (thin line) fitted to the observations (thick line).

Table 1: Fitted parameters by the four-mass-component MN potential. M_i in $10^{11}M_\odot$; a_i, b_i in kpc; ρ_i^0 in $M_\odot$ pc^{-3}; σ_i^0 in $10^3 M_\odot$ pc^{-2}.

	MW	N253	IC342	N891	N1808	N3079	N4565	M51	N5907	N6946
	Sb	Sc	Sc	Sb	Sbc	Sc	Sb	Sc	Sc	Sc
M_1 (Halo)	5.0	2.0	3.0	2.0	0	3	5	0	3.5	3.0
$a_1 = b_1$	15	15	15	20	—	18	15	—	15	20
ρ_1^0	.0035	.0003	.0020	.0006	0	.0012	.0035	0	.0025	.0009
M_2 (Disk)	1.5	1.1	1.0	1.4	0.80	1.50	2.2	1.3	2.5	1.65
$a_2 (b_2 = 0.5)$	6.0	5.0	5.5	5.0	4.2	5.0	7.0	4.7	7.5	6..0
ρ_2^0	2.0	2.1	1.9	2.7	2.2	2.9	2.1	2.8	2.1	2.2
M_3 (Bulge)	0.15	0.16	0.14	0.12	0.10	0.10	0.25	0.30	0.25	0.10
$b_3 (a_3 = 0)$	0.9	1.0	1.2	0.8	1.0	1.10	1.0	1.4	1.5	1.10
ρ_3^0	5.0	3.8	1.9	5.5	2.4	1.8	6.0	2.6	1.8	1.8
σ_3^0	5.9	5.1	3.1	6.0	3.2	2.6	8.0	4.9	3.5	2.6
M_4 (Cen.)	0.055	0.035	0.015	0.05	0.055	0.08	0.05	0.08	0.05	0.040
$b_4 (a_4 = 0)$	0.15	0.16	0.15	0.16	0.22	0.16	0.20	0.25	0.25	0.12
ρ_4^0	390	200	110	290	120	470	290	120	80	550
σ_4^0	78	44	21	62	36	99	40	41	26	88

by the massive spherical mass.

Hence, the circular-motion approximation assumed here would be reasonable in so far as the zero-th-order mass distribution in the central region of galaxies is concerned.

1.3.2 Higher Central Density in Earlier Hubble Type Galaxies

It is interesting to examine if the parameters listed in Table 1, particularly those related to bulges, are correlated with the Hubble type. In Fig. 2 we show some correlations. The central density of the disk component (ρ_2^0) is almost constant. It is conspicuous that bulges for Sb galaxies have much greater central density than Sc. This indicates that the morphologically "smaller-bulge" for later-type galaxies is due to lower density of bulge, but not due to difference in scale radii. In fact, bulge radius b_3 and the ratio b_3/a_2 rather increase toward Sc. The central density ρ_4^0 also show a similar behavior to ρ_3, except for NGC 3079 and NGC 6946. The high density for NGC 3079 might be related to formation of the central compact object associated with nuclear activity and jet. Among the other parameters, M_2 is well correlated with a_2, and M_3 and M_4 are also correlated with a_3 and a_4, respectively.

1.3.3 Evolution of Bulges and Central Regions

The concentric "bulge-in-bulge" structure suggests that the central mass condensation during the dynamical evolution of galaxies was not single-fold, but it may have occurred recurrently under different conditions. In addition to a bulge formation during the initial contraction (e.g.,

Figure 2: The central densities plotted against galaxy types. Sb galaxies have higher density, corresponding to their larger (more massive)bulges, than Sc galaxies.

Eggen et al. 1962), recurrent accretion of gas and subsequent starbursts due to barred-shocks (Noguchi 1988; Wada and Habe 1992) would have resulted in formation of a denser stellar component within the bulge. According to a viscous-disk contraction model with on-going starformation (Saio and Yoshii 1990), a central density excesses over an exponential disk and a peaked RC at a several-hundred-pc radius is obtained. It is likely that the viscosity time scale in the central 100 – 200 pc is much shorter than that in the disk due to stronger shear motion, while the starformation time scale is similar. This may result in a higher-density stellar condensation, and would account for the multi-bulge structure.

2 CO-Line Width - Luminosity Relation

2.1 CO-Line Tully Fisher Relation

The HI-line width - luminosity relation (Tully-Fisher relation) is one of the most powerful tools to measure distances to galaxies (Tully & Fisher 1977; Aaronson et al. 1986; Pierce & Tully 1988; Kraan-Korteweg et al. 1988; Fouqué et al. 1990; Fukugita et al. 1991). However, distances to galaxies so far reached by HI observations are limited to around 100 Mpc, or $cz \sim 10,000$ to 15,000 km s^{-1} even with the use of the world-largest telescopes (Schöniger and Sofue 1993). We have no routine method to determine distances to galaxies beyond this distance, at which angular resolution of a few arc minutes in HI observations becomes too large to resolve individual galaxies in a cluster. Interferometers like VLA are not useful for the purpose because of the limited number of spectral channels (velocity resolution). Furthermore,

Figure 3: CO vs HI line profiles for NGC 891 (left), and correlation between distances derived using HI and CO-line Tully Fisher Relations for nearby galaxies (middle) and galaxies up to 100 Mpc (right).

red-shifted HI frequency results in increases in beam size as well as in interferences, which also makes resolution of distant cluster galaxies difficult. Moreover, HI line profiles are easily disturbed by interactions among galaxies, which is inevitable in the central region of a cluster, causing uncertainty in the HI line profiles for the Tully-Fisher relation. On the other hand, molecular gas is tightly correlated with the luminous stellar disk, so that it is less affected by the tidal interaction. The molecular gas is distributed enough to a radius of several to ten kpc, so that the integrated line profiles manifest the maximum velocity part of the rotation curve (Sofue 1992).

Molecular-line observations at millimeter wavelengths, particularly in the CO-line emission at 115 GHz, can be achieved with much sharper beams. Therefore, we will be able to resolve individual member galaxies in a cluster more easily, which makes it possible to avoid contamination by other member galaxies in a beam. Moreover, the larger is the redshift of an object, the lower becomes the CO frequency, which results in a decrease in the system noise temperature due to the atmospheric O_2 emission near 115 GHz: the more distant is a galaxy, the lower becomes the noise temperature.

Dickey and Kazes (1992) have addressed the use of CO line widths instead of and/or in supplement to HI observations, and proposed the CO-line Tully-Fisher relation as an alternative to the HI Tully-Fisher relation. The CO-line width - luminosity relation has been established for the local distance calibrators and tens of nearby galaxies (Sofue 1992; Schöniger and Sofue 1993) (Fig. 3). In these works, we have have shown that the CO-line measurements can be used as an alternative to HI by deriving a good linear correlation between CO and HI linewidths for the galaxies in the sample. Only a disadvantage of the use of CO line would be the sensitivity, particularly for distant galaxies. Actually, we need a few mK rms data for line-width measurements at a velocity resolution of 10 km s^{-1} for normal galaxies beyond $cz \sim 10,000$ km s^{-1}, which requires long integration times. Such observations are possible only by a long-term project with the use of the world-largest mm-wave telescopes.

On the basis of these studies, Sofue et al (1996) have conducted a long-term project to observe $^{12}CO(J = 1 - 0)$ line profiles for distant cluster galaxies using the Nobeyama 45-m telescope and the IRAM 30-m telescope. Here, We summarize their result, and details will be presented in Sofue et al (1996). We also obtained high-quality optical imaging of detected galaxies in CO in order to measure the inclination and magnitude using the Canada-France-Hawaii 3.6-m telescope. In this paper, we report a first-step result of the measurement of CO line profiles in order to demonstrate that the line profiles can be obtained in a routine work within a reasonable integration time, and that the distances can be obtained by applying the Tully-Fisher relation relation. We also report on optical imaging observations of several CO-detected galaxies, and try to obtain a possible value of the Hubble constant for galaxies with $cz \sim 20,000$ km s^{-1}.

2.2 CO-Line Observations

Observations of the ^{12}CO$(J = 1 - 0)$ line of distant cluster galaxies were made from 1994 January 14 to 23, 1994 December 9-12, and 1995 January 6-10 and March 13-17, using the 45-m telescope of the Nobeyama Radio Observatory. We observed about fifty galaxies, which had $cz \sim 10,000$ to 28,000 km s^{-1}and relatively strong far-IR emission at 60 and 100 μm, selected from the NED (NASA Extragalactic Database). Among the galaxies, sufficient quality data have been obtained for fifteen galaxies, and the CO line were detected in seven galaxies. Among the seven, good CO line profiles were obtained for three galaxies with a sufficient signal-to-noise ratio for determining the velocity width.

The antenna had a HPBW of $15''$, and the aperture and main-beam efficiencies were $\eta_{\rm a} = 0.35$ and $\eta_{\rm mb} = 0.50$, respectively. We used two SIS receivers with orthogonal polarizations which were combined with 2048-channel acousto-optical spectrometers of 250 MHz bandwidth with a velocity coverage of 650 $(1+z)$ km s^{-1}. After binding up every 32 channels in order to increase the signal-to-noise ratio, we obtained spectra with a velocity resolution of 10.2 km s^{-1}. The system noise temperature (SSB) was 300 to 400 K. The calibration of the line intensity was made using an absorbing chopper in front of the receiver, yielding an antenna temperature ($T_{\rm A}^*$), corrected for both the atmospheric and antenna ohmic losses. We used an on-off switching mode, and the on-source total integration time was about 1-4 hours for each galaxy. The rms noise of the resultant spectra at velocity resolution of 10 km s^{-1}was typically 2 mK in $T_{\rm A}^*$. The pointing of the antenna was made by observing nearby SiO maser sources at 43 GHz every 1 to 1.5 hr, and was typically within $\pm 3''$ during a good weather condition which were attained for about one fourth of the allocated observing time.

We have detected the CO-line emission for six galaxies, CGCG 1113.7+2936, CGCG 1448.9+1654, CGCG 1417.2+4759, CPG 60451, NGC 6007, and IC 2846. We obtained marginal detection for several galaxies including a possible detection for IRAS 14210+4829. Observed CO spectra for the detected galaxies at a velocity resolution of 10 km s^{-1} are shown in Fig. 4. The intensity scale used in this paper is the antenna temperature. We have also performed CO line observations using the IRAM 30-m telescope, and detected CGCG 1417.2+4759. We also show the spectrum of these galaxy taken with the 30-m telescope in Fig. 4. All the obtained profiles show a typical double-peaked emission, characteristic of a rotating ring. From these data we measured the line width, peak antenna temperature, and line intensity for individual galaxies.

2.3 Optical Observations

High-quality optical images of CGCG1417, CGCG1448, and CPG 60451 at V, R and I bands were obtained using the Canada-France-Hawaii 3.6-m Telescope on June 30 - July 1, 1995. Additional images have been taken with the 105-cm Schmidt telescope of the Kiso Observatory in January 1994. Using these data, we have determined apparent magnitude and inclination

Figure 4: CO line profiles for six detected galaxies and a marginal detection (IR 14210) in channel-Ta plane.

Figure 5: Optical images in R band of galaxies CGCG 1417 (left), CGCG 1448 (middle), and CPG60451 (right).

of the galaxies.

Imaging observations were made in V, R_C, I_C bands using the Canada-France-Hawaii 3.6-m Telescope. The CCD effective imaging area was 2048×2048 pixels with a pixel size of $15\mu\text{m} \times 15\mu\text{m}$. The camera covered a sky area of $3' \times 3'$ with a resolution of $0.086''$ per pixel. The FWHM seeing size was $0.6' - -0.8''$, which is small enough to determine the morphology of the observed galaxies. The dome screen was exposed to obtain flat frames. The large field of view gives a sufficiently large sky area around the galaxies to allow an accurate sky-subtraction.

Optical R_C band images are shown in Fig. 5. The isophotal maps were fitted with ellipses to obtain the isophotal magnitudes and axial diameters. To evaluate the TF relation we need the velocity width to be corrected for the inclination i and for redshift effect into an edge-on value at the rest frame. We obtain an intrinsic velocity width in the rest frame referred to the galaxy corrected for the inclination by

$$W_R^i = W_0 \sin i,$$

where W_0 is the rest-frame velocity width given by

$$W_0 = W_{\text{rest}} = c(1+z)\Delta\nu_{\text{obs}}/(115.2712 \text{ GHz}).$$

and ν_{obs} is the observed line width in frequency. We obtain the inclination i of a galaxy from the conventional formula given by Hubble (1926) for oblate spheroid, $\cos^2 i = (q^2 - q_0^2)/(1 - q_0^2)$ with $q = b/a$ and $q_0 = c/a$, where a, b, and c are the lengths of three axes of the spheroid. Here, we adopt $q_0 = 0.20$ for the present analysis. The Galactic absorptions A_B, internal absorption correction A_i, and the K-correction have been applied to obtain the corrected total

Table 2: Distance modulus, Distance, and Hubble ratio for the detected galaxies.

Galaxy	$m-M$ mag		D Mpc		$H =< V_C/r >$ km s^{-1} Mpc^{-1}	
CGCG 1417	36.46	±.13	195.86	±11.90	110	±7
CGCG 1417 (IRAM 30-m)	37.16	±.09	270.55	±11.36	80	±3
CGCG 1448	36.95	±.08	245.14	±9.28	55	±2
PGC 60451	37.33	±.17	293.21	±23.28	51	±4

magnitude

$$m_{\mathrm{T}}^{b,i} = m_{\mathrm{T}} - A_B - A_i - K.$$

2.4 Distances and the Hubble Ratio

We adopt the zero point of the TF relation given by Pierce & Tully (1992) for R and I and by Shimasaku & Okamura (1992) for V band, and obtained the absolute magnitude. We, then, derived distance modulae, distances, and Hubble ratios V_C/r for individual galaxies. Here, the recession velocity V_C is the value with respect to the CMB rest frame. Averaged values in the V, R_C, and I_C band results are also shown with their dispersions in Table 2.

The NRO and IRAM results are different for CGCG 1417. Since the velocity coverage of IRAM data is wider, the IRAM result may be more reliable, and we prefer the H value of 80 for this galaxy. For the other two galaxies, H values are rather small. However, we note that the present results are still preliminary, and we need further observations to give conclusive values.

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