NUCLEAR-TO-DISK ROTATION CURVES AND MASS-TO-LUMINOSITY RATIO IN GALAXIES [1]

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ABSTRACT

High-resolution nuclear-to-outer rotation curves for Sb, SBb, Sc, and SBc galaxies show generally a steep nuclear rise and flat rotation from the disk to halo. The high-velocity central rotation indicates massive core within bulges. Since this characteristics is common to most galaxies, the high-velocity central rotation cannot be due to a particular orientation of non-circular motion. Using these rotation curves, we derive the distributions of surface-mass density, and compare directly with observed surface-luminosity distributions. The mass-to-luminosity ratio (M/L) remains constant in the outer bulge and disk, while it increases toward the halo, indicating the massive halo. In the central region, the M/L also increases steeply toward the center, reaching by an order of magnitude greater value than the disk value, which may indicate a massive core of radius ~ 100 parsecs and mass of $\sim 10^9 M_\odot$. The core may be an object linking a bulge and a massive black hole.

1. INTRODUCTION

Rotation curves are the principal tool to derive the axisymmetric component of the mass distribution in spiral galaxies for the first-order approximation. Higher-order non-axisymmetric fluctuations such as spiral arms and bar may be superposed, which could, however, be estimated only through extensive numerical simulations of velocity fields and gas distributions for individual galaxies, but is out of the scope of this paper.

Rotation curves in the disk and outer regions have been obtained based on optical and HI-line spectroscopy (Rubin et al 1980, 1982; Bosma 1981; Clemens 1995; Persic et al 1996; Sofue 1996, 1997; Honma and Sofue 1997). These rotation curves have been used to estimate the mass distribution in the disk and halo (e.g., Kent 1987, 1992). However, the inner-most rotation curves are not necessarily well investigated yet in high accuracy because of the lack of HI gas, as well as because of the contamination of strong bulge light when photographic plates were used.

In order to derive inner rotation curves, species like the CO molecules will be most convenient for its high concentration in the center, for the available high-resolution spectroscopy, and for its negligible

[1]Presented at 32nd COSPAR General Assembly, Session E1.2, 1998 July 15-17, Nagoya: To appear in proc. "AGN-Normal Galaxy Connection", ed. A. Kinney

extinction even toward the nuclear dusty disk. We have been, therefore, using high-resolution CO-line data to obtain most-completely-sampled rotation curves for nearby galaxies (Sofue 1996, 1997, Sofue et al 1997, 1998). In deriving rotation velocity, we have applied the envelope-tracing method, which traces the maximum terminal velocities in position-velocity diagrams along the major axes (Sofue 1996, 1997). Recent CCD Hαline spectroscopy has also made us available with accurate rotation curves for the inner regions, because of the larger-dynamic range, as well as for easier subtraction of the bulge continuum emission (Rubin et al 1997; Sofue et al 1998).

Fitting of rotation curves by model potentials have been widely applied to discuss the mass distribution (e.g., Kent 1987; Sofue 1996). However, the decomposition of an observed rotation curve using model potentials is found to be not unique: For example, an exponential disk and a Plummer's potential result in nearly identical rotation curves, while their mass distributions are quite different from each other.

Hence, in order to investigate the mass distribution and the mass-to-luminosity ratio in galaxies without intervened by any potential models, it will be more convenient to use the surface-mass density directly calculated from observed rotation curves. On the other hand, surface-luminosity distributions have been observed for many galaxies in high accuracy in optical and near-infrared ranges. Both the bulge and disk components are known to be well fitted by exponential law luminosity profiles (de Jong 1996; Heraudeau 1996).

In this paper, we present high-accuracy rotation curves for Sb, SBb, Sc and SBc galaxies, and discuss their general characteristics. We derive radial distributions of dynamical surface-mass density, and compare with the surface photometry. We also derive the mass-to-luminosity ratio and discuss its radial variation.

2. UNIVERSAL PROPERTIES OF NUCLEAR-TO-OUTER ROTATION CURVES

The Milky Way

The rotation curve of the Milky Way Galaxy is shown in Fig. 1. Fig. 1a is a usual plot in a linear scale. Genzel et al (1997, 1998) have shown that the velocity dispersion of stars within the central 10 pc does not decline to zero, but behaves in a Keplerian fashion, indicating the existence of a massive black hole. Combining the velocity dispersion and high-velocities observed in the CO line emissions, we may raw a "rotation curve" of the Milky Way as shown in Fig. 1b in logarithmic scales. Here the velocity dispersion and rotation velocity have been taken to be identical, both representing the mass distribution. Since evidences for nuclear massive black holes have been accumulated for many other galaxies (Miyoshi et al 1995; Faber 1998), we may also speculate that the central rotation curves of galaxies would be more or less similar to that as shown in Fig. 1b.

How to derive rotation curves

Besides the Milky Way, it has been widely believed that inner rotation curves behave in a rigid-body fashion (Rubin et al 1980, 1982; Persic et al 1996). For example, the bulge and inner bulge components are not detected in the so-called "universal rotation curves" presented by Persic et al (1996) based on about a thousand optical and HI rotation curves observed by Mathewson et al (1996), whose major purpose was, however, to discuss the dark halo. These RCs appear to behave very differently from that of the Milky Way's rotation in the inner disk and bulge regions.

A question may arise, either if the Milky Way is an exception, or something is missing in the inner

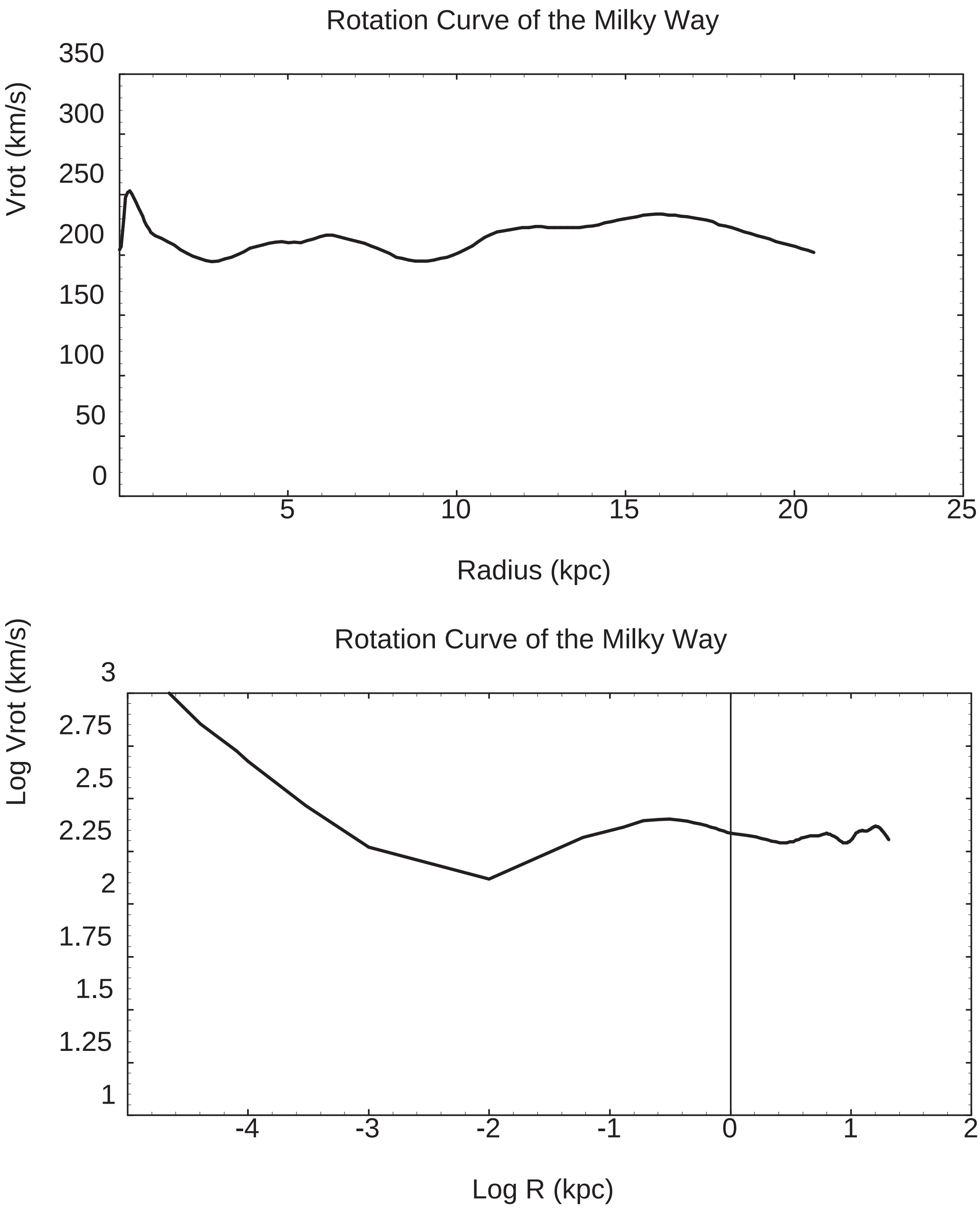

Fig. 1. (a) "Usual" rotation curve of the Milky Way plotted in linear scale. (b) "Probably true" rotation curve plotted in a logarithmic scale, which obeys the Keplerian near the center due to the massive black hole. Many galaxies would have similar behavior of rotation velocity in the center. Note that central zero-velocity has been adopted merely by a custom to draw a curve linking positive and negative velocities in both sides of the nucleus on PV diagrams.

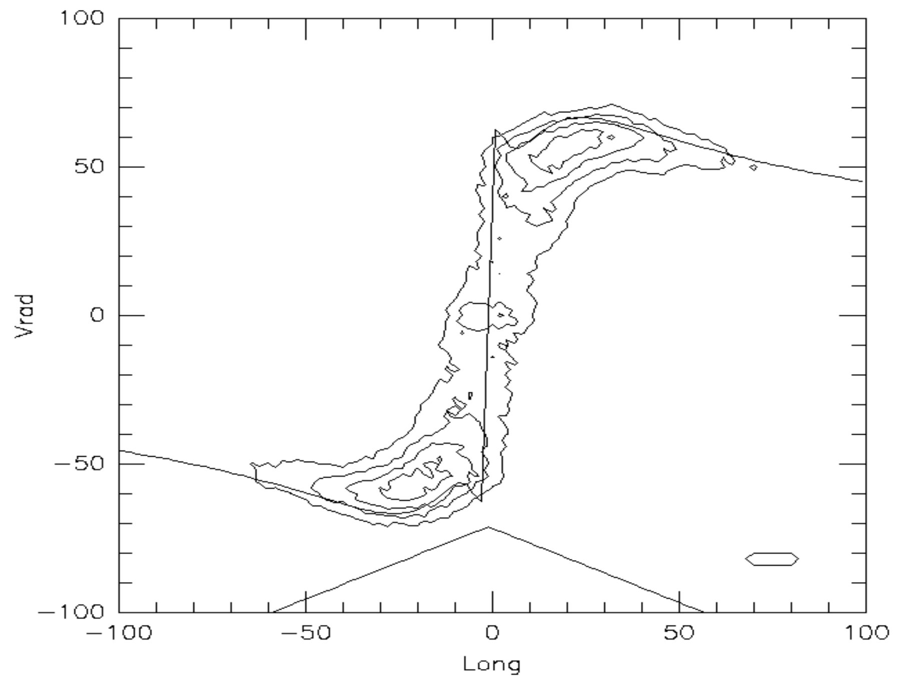

Fig. 2. Simulation of a position-velocity diagram (contours) from an assumed rotation curve (full line) and gas distribution (semi-logarithmic density profile at bottom) for a finite beam and velocity resolution with some artificial noise added. Coordinates are arbitrary. The bulge and inner-disk kinematics may be easily missed, if we trace the peak-intensity positions on PV diagrams.

parts of these "universal" rotation curves. In order to clarify this, we have simulated position velocity diagrams based on an assumed rotation curve and gas distribution for finite velocity and angular resolutions with some noise. Fig. 2 shows an example, where the gas distribution is exponential and the rotation curve comprises the bulge and disk components. No bulge component shows up in this simulated PV diagram. This suggests that the central kinematics may be easily missed, if we trace the peak-intensity positions in PV diagrams, and that a high-resolution PV diagram of species, which is highly concentrated to the center, is necessary to derive nuclear rotation curves.

Most-completely-sampled rotation curves

We have been undertaking compilation of high-resolution CO-line PV diagrams, both from our own observations and from the literature, and combined with the existing HI and optical rotation curves. We have also obtained CCD spectroscopy in the Hα and [NII] line emissions of the central regions of galaxies. We also adopted the 'envelop-tracing method' to derive rotation curves from the PV diagrams (Sofue 1996, 1997). In Fig. 3 we show the thus obtained most-completely sampled rotation curves for Sb and Sc galaxies (Sofue 1996, 1997; Sofue et al 1997, 1998). Dashed curves are for barred galaxies. In Fig. 4 we show rotation curves for Sb and Sc galaxies separately. In so far as our sample galaxies, whose central rotation curves have been derived from high-resolution CO line data, are concerned, the rotation characteristics of spiral galaxies is essentially the same as that of the Milky Way.

Sb galaxies

All Sb galaxies have rotation curves with a very steep rise in the central 100-200 pc region, often associated with a sharp peak at radii $r \sim 100 - 300$ pc. The rotation velocity, then, declines to a

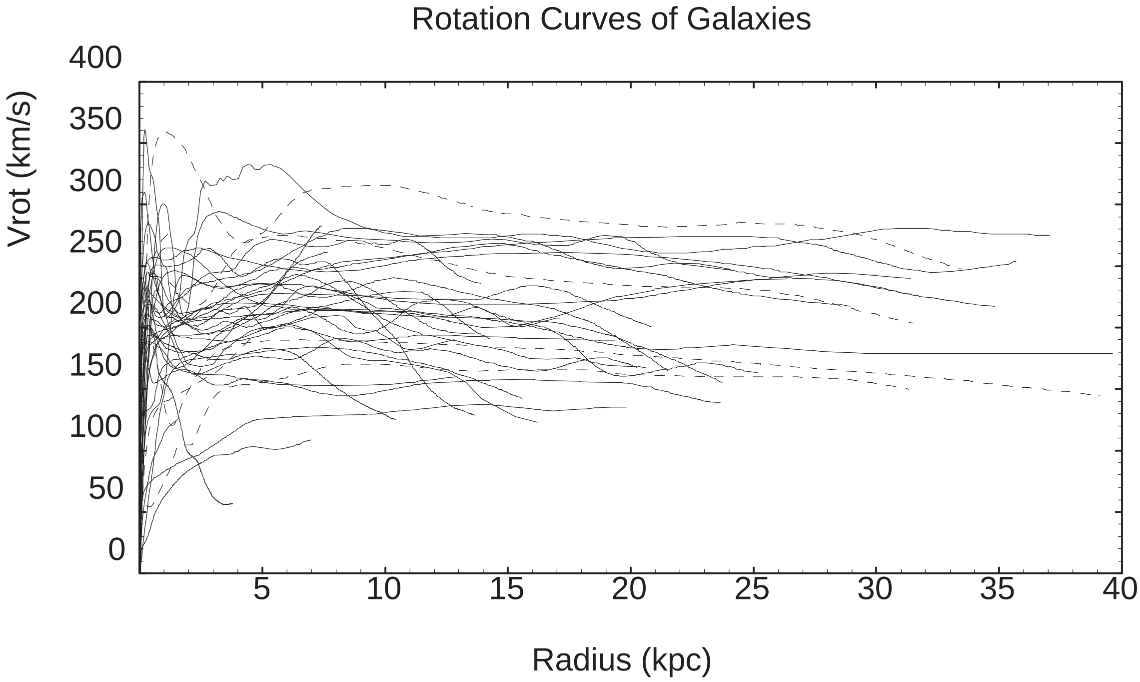

Fig. 3. Most-completely-sampled rotation curves of Sb and Sc galaxies obtained by using CO, Hα and HI-line data. Dashed lines are for barred galaxies.

minimum at $r \sim 1$ kpc, and is followed by a gradual rise to a broad maximum at $r \sim 2 - 10$ kpc, corresponding to the disk. The outermost part are usually flat, while some galaxies like the Milky Way show a declining outer rotation (Honma and Sofue 1996, 199). In general, rotation curves for Sb galaxies are similar to that of our Milky Way Galaxy. There appears no characteristic difference between normal Sb and barred SBb galaxies.

Sc galaxies

Sc and SBc galaxies show similar rotation curves, while having slower velocities than Sb, and the rotation velocities are more spread from ~ 100 to ~ 200 km s^{-1} among galaxies. Massive Sc galaxies show a steep nuclear rise, while less-massive galaxies have a more gradual rise. They also have a flat rotation until their outer edges.

Barred galaxies

Some galaxies in Fig. 3 are barred galaxies. Typical SBb galaxies are NGC 1097, NGC 1365, and NGC 6674; SBc galaxies are NGC 3198, NGC 5236, and UGC 2855. Except that the SBb galaxies have higher rotation velocity than SBc, there appears no particular difference in their general properties: The rotation property of the barred galaxies is almost the same as those for normal Sb and Sc galaxies.

Irregular galaxies

Rotation curves for irregular galaxies have been obtained for NGC 3034, NGC 4631 and NGC 4945. NGC 3034 (M82) shows a very exceptional behavior of rotation: it has a steep nuclear rise as usual, but decreases smoothly after its nuclear peak, obeying the Keplerian law. NGC 4631 is an interacting dwarf amorphous galaxy, showing a rigid-body increase of rotation velocity. However, since this galaxy is edge on, it is not clear, if the CO gas is missing near the nucleus, which might

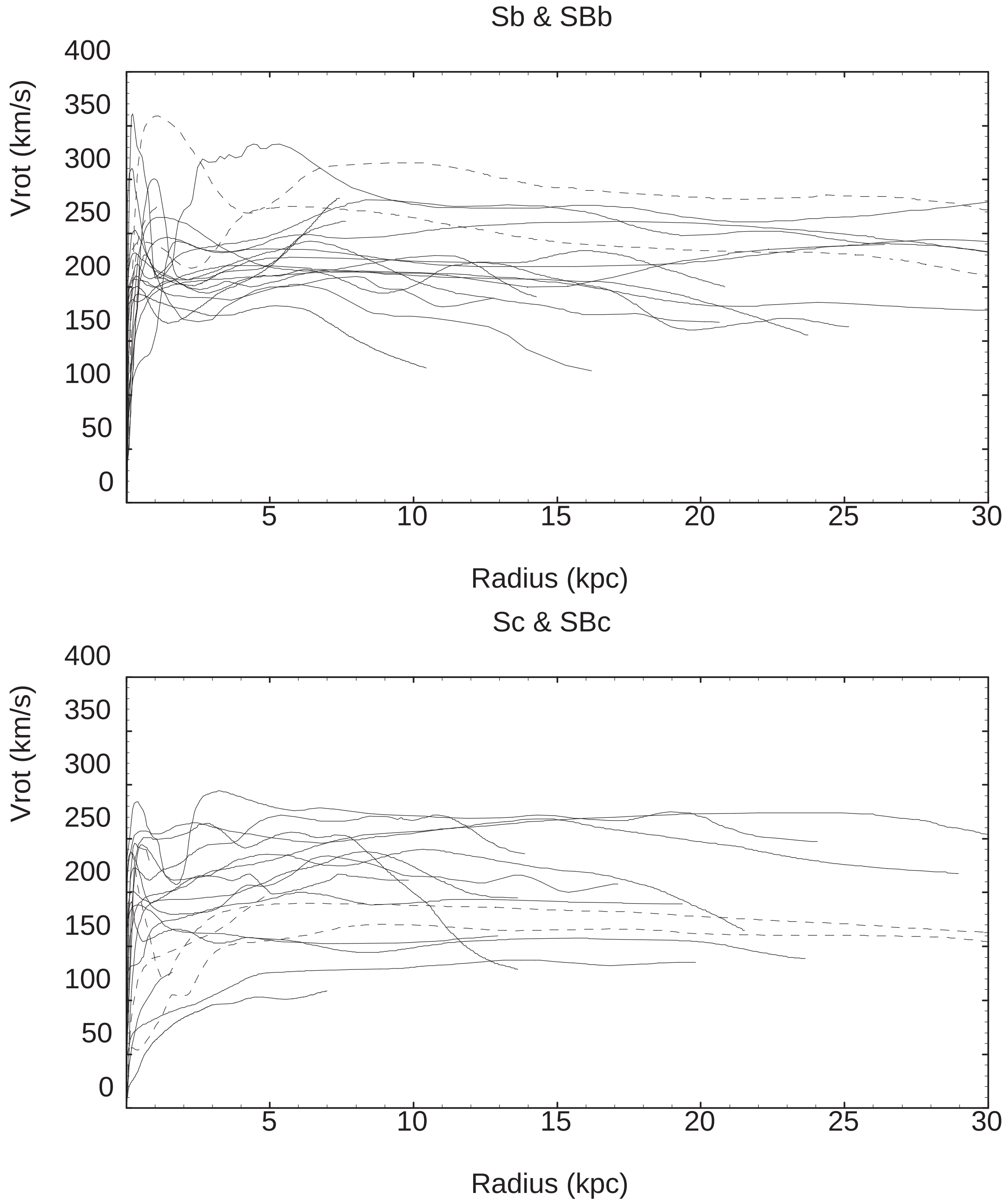

Fig. 4. (a) 16 Sb (full lines) and 3 SBb (dashed) galaxies. (b) 16 Sc (full lines) and 3 SBc (dashed) galaxies; Note that small-mass galaxies, whose maximum disk velocities are 100 to 200 km s^{-1}, tend to show mild rise.

have resulted in a pseudo rigid-body rotation. NGC 4945 shows a quite normal rotation with a steep nuclear rise and flat disk rotation.

Universal property: Steep nuclear rise and non-zero velocity at center

Our data in Fig. 3 and 4 are based mainly on CO line data, which traces the circular rotation of the innermost region of galactic disks. Galaxies observed at high resolutions with the Nobeyama milimeter Array show a very steep nuclear rise. Moreover, nearer galaxies with higher linear resolution tend to have a steeper nuclear rise, which would suggest that farther galaxies might not be resolved of the central steeper rise. From these facts we may conclude that the steep nuclear rise in the central region is a universal property for Sb and Sc galaxies, regardless the existence of a bar. Recent optical CCD observations have also shown the nuclear rise (Rubin et al 1997; Sofue et al 1998), in agreement with the CO results.

It is also interesting that the rotation velocity in many galaxies does not decline to zero at the nucleus. This indicates that the mass density increases toward the nucleus more rapidly than expected from exponential distribution of surface-mass density. We mention that the widely adopted zero-velocity at the center might be merely due to a custom to draw a curve by linking positive and negative velocities from both sides of the nucleus.

The extremely high frequency of galaxies showing the nuclear rise indicates that the high velocity is not due to an end-on view of non-circular motion by chance. Note that the probability to look at a bar end-on is much smaller than that of side-on view, which should result in a larger probability for apparently slower rotation than circular velocity. Therefore, the mass estimated from the circular assumption would be even underestimated in many galaxies, if they contain a bar.

Activity and rotation curves

No particular correlation has been found of the rotation curves with central activities. Our sample includes starbursts (e.g., NGC 253, NGC 1808), Seyferts (NGC 1068, NGC 1097), LINERs (NGC 3521, NGC 4569, NGC 7331), galaxies with jets (NGC 3079), and galaxies with massive black holes (Milky Way, M31, NGC 4258). Only an exception is the starburst galaxy NGC 3034 (M82), which shows a 'usual' nuclear rise but is followed by a Keplerian disk.

3. MASS DISTRIBUTION AND MASS-TO-LIGHT RATIO

Four mass components

Using the rotation curves, we have calculated radial distributions of surface-mass density (SM), assuming both spherical symmetry and a flat disk (Takamiya and Sofue 1998). We found that both assumptions resulted in a similar mass distributions, differing at most by a factor of 1.5. We stress that a complete set of nuclear-to-outer rotation curve is necessary to calculate the SM distribution. Fig. 5a and b show the thus obtained radial distributions of surface-mass density for Sb and Sc galaxies for a disk assumption. The error in the mass estimate is approximately $\pm 20\%$, which arises from the error in the rotation velocity, and the systematic error depending on the disk/sphere assumption is about a factor of 1.5 at most, as demonstrated in Fig. 6.

The thus calculated surface-mass density is well represented by four major components: (1) a nuclear dense core, (2) a bulge, (3) an exponential disk, and (4) a halo. The surface mass density in the inner 1 kpc increases toward the center according to the bulge. It shows a particularly steep increase inside

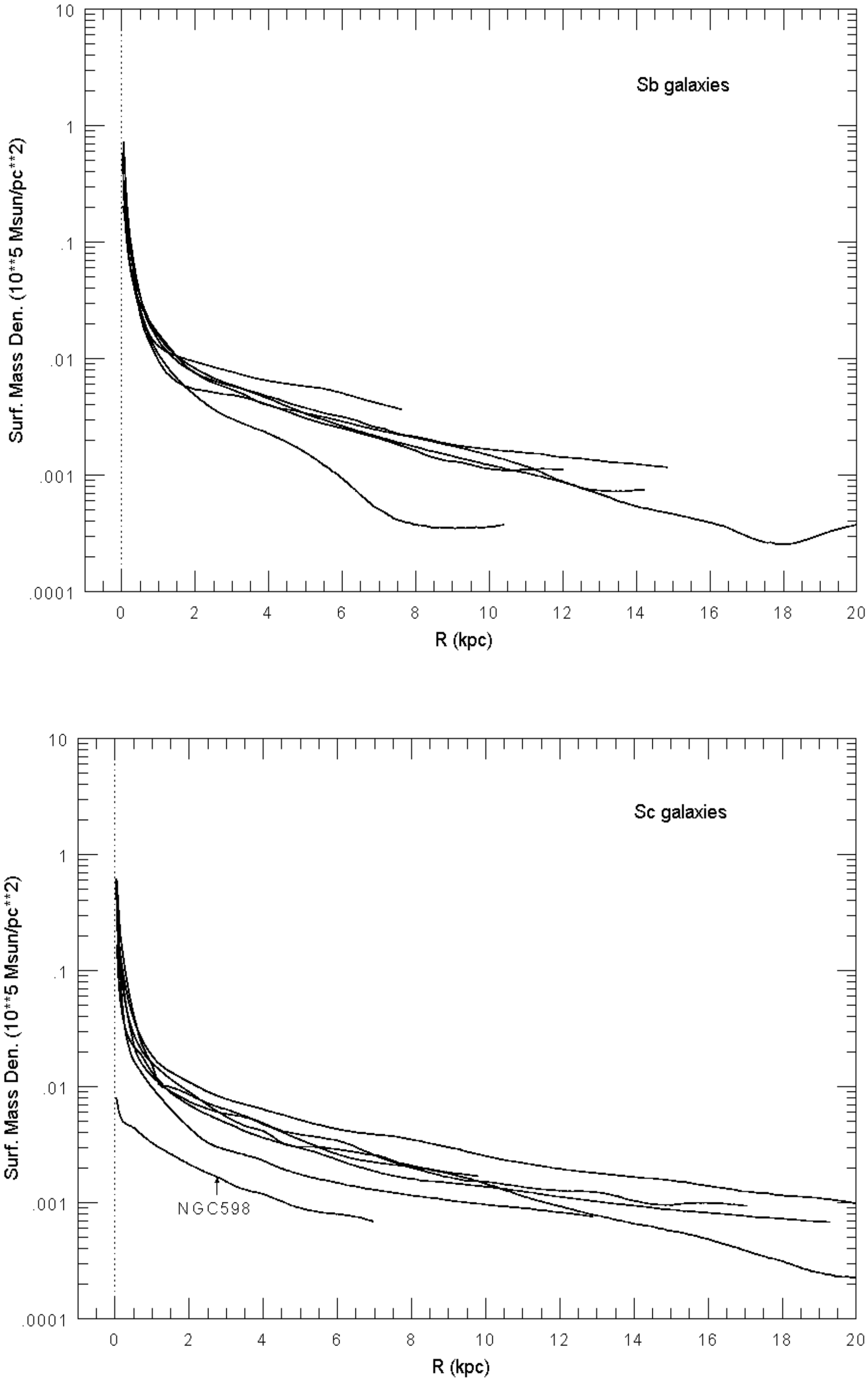

Fig. 5. Surface mass density of Sb and Sc galaxies as calculated for disk assumption (Takamiya and Sofue 1998).

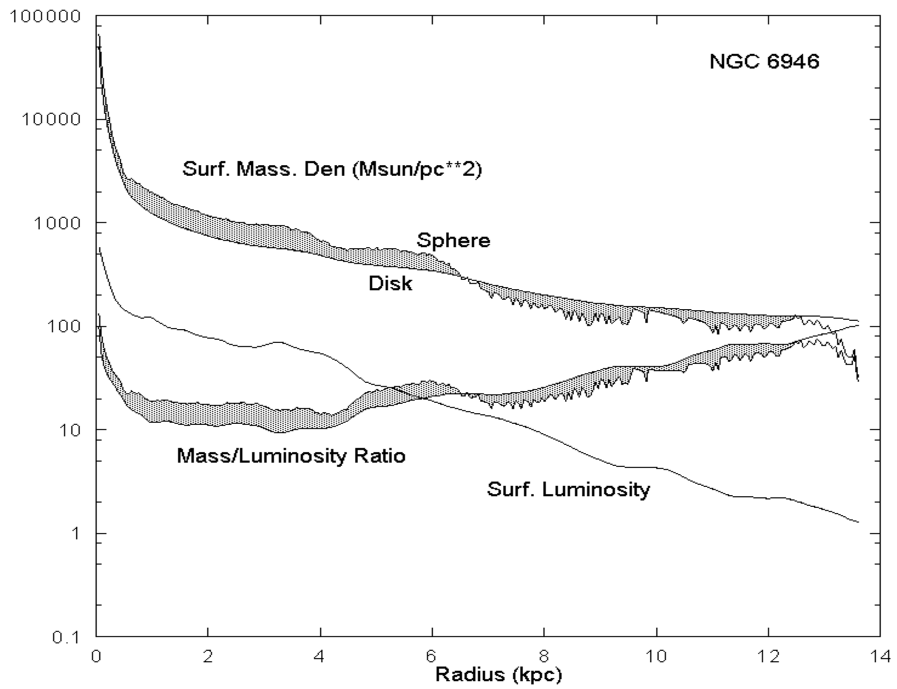

Fig. 6. Radial distributions of surface mass density for a spiral galaxy NGC 6946 calculated both for disk and spherical assumptions, indicated by two lines filled with shadows. The true mass distribution will lie between these two lines. Observed B-band surface luminosity is shown by the thin line. The mass-to-luminosity ratio is also shown by two lines filled with shadow. The ML ratio in the central region exceeds that of the disk and outer bulge, suggesting a dark core mass. It also increases toward the halo due to the dark halo.

0.3 kpc, which cannot be represented by an exponential law as indicated from surface photometry.

Common mass distribution regardless the activity

Sb and Sc galaxies, including some barred galaxies, are found to show similar mass distributions. Also, the central activities appear to be not directly correlated with the mass distribution. Note that the sample includes galaxies showing starburst (NGC 3034), Seyfert (NGC 1068, NGC 2841, NGC 4569), LINER (NGC 3521, NGC 4569, NGC 7331), jets (NGC 3079), or black holes (Milky Way, NGC 4258).

Radial variation of Mass-to-Luminosity ratio

We have calculated the M/L ratio (Takamiya and Sofue 1998) using the calculated surface-mass distributions and observed surface-luminosity data from the literature (e.g., Kodaira et al 1990; de Jong 1996; Heraudeau et al 1997). Fig. 6 plots the obtained distribution of M/L ratio for the spiral galaxy NGC 6946. The M/L ratio in the disk remains almost constant at $R \sim 0.5$ to 7 kpc. The outer-disk M/L increases gradually outward, indicating the massive dark halo. The normal bulge component, clearly visible in the surface-mass distribution at $R = 0.5 - 1.5$ kpc, has almost the same M/L as the disk, implying that the bulge stars have a similar M/L to disk stars. It should be stressed, However, that the M/L increases toward the center very steeply. This may indicate either a dark mass concentration in the central 100 pc, or a significant extinction of the luminosity. Since NGC 6946 is nearly face on, the latter case would be not so realistic, suggesting preferably a dark massive core.

4. DISCUSSION

Many spiral galaxies, for which sufficiently high-resolution nuclear rotation curves are available, have similar rotation curves to that of our Galaxy: (1) Steep nuclear rise, or more likely starting from high velocity (e.g., c); (2) bulge component; (3) broad maximum by the disk; and (4) flat halo component. These correspond to the four mass components: a nuclear core, a bulge, disk, and massive halo. The calculated mass distributions for the sample galaxies have shown no particular correlation with their central activities.

The steep increase of M/L at $R < 100$ pc observed for some galaxies may imply that a galactic bulge contains a 'dark massive core'. The dark core has a scale radius of ~ 100 pc or less, and a mass $\sim 10^9 M_\odot$, where the mass-to-luminosity ratio exceeds that of the mean disk and bulge values by an order of magnitude. The origin of the dark core, however, remains open to discussion. A dark core could be an object linking the galactic bulge and a massive black hole, having a crucial implication for the formation and evolution of galactic bulges.

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