Accurate Rotation Curves and Distribution of Dark Matter in Galaxies*

Yoshiaki Sofue
Institute of Astronomy, University of Tokyo, Mitaka, Tokyo 181-8588, Japan.

February 23, 2011

Abstract

We present high-accuracy rotation curves, which show a steep nuclear rise and high-velocity central rotation, followed by a broad maximum in the disk and flat part. We use the rotation curves to directly calculate the radial distribution of surface mass density, and obtain radial variations of the mass-to-luminosity ratio (M/L). The M/L ratio and, therefore, the dark mass fraction (DMF) is not constant at all, but varies within the bulge, increases already within the disk, and rapidly from the disk toward halo. In some galaxies, the DMF within the bulge increases inward toward the center, indicating a massive dark core.

1 Introduction

Rotation curve is the principal tool to derive the axisymmetric distribution of mass in disk galaxies in the first-order approximation. Rotation curves have been obtained by optical and HI-line spectroscopy (Rubin et al 1980, 1982; Bosma 1981; Mathewson et al 1996; Persic et al 1996). However, the inner rotation curves have been not thoroughly investigated yet, not only

*To appear in the Proceedings of XIXth Moriond Astrophysics Meeting "Building Galaxies: from the Primordial Universe to the Present", Les Arcs, March 13-20 1999. ed. F.Hammer et al. (Editions Frontieres, Gif-sur-Yvetter)

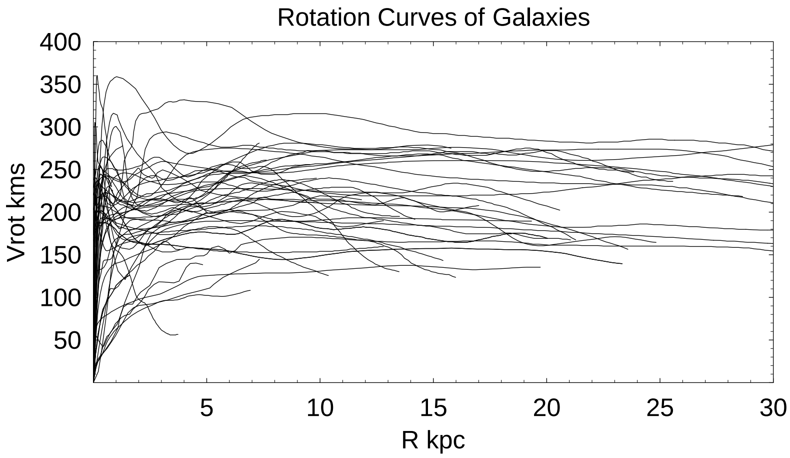

Fig. 1a. Most-completely-sampled rotation curves of Sb, Sc, SBb and SBc galaxies obtained by using CO, Hα and HI-line data.

because the concern in these studies has been on the massive halo, but also for the difficulty in observing inside central bulges. We have shown that the CO molecular line is useful for deriving central kinematics for its high concentration in the center and low extinction (Sofue 1996, 1997, Sofue et al 1997, 1998: Papers I to IV). Recent CCD Hα line spectroscopy has also made us available with accurate rotation curves for the inner regions (Rubin et al 1997; Sofue et al 1998). In this paper, we present high-accuracy rotation curves, and discuss their general characteristics. We derive surface mass distributions, and discuss the radial variation of mass-to-luminosity ratio and the dark mass fraction.

2 Universal Properties of Rotation Curves

2.1 Central-to-Outer Rotation Curves

Besides the Milky Way, it has been widely believed that inner rotation curves behave in a rigid-body fashion. In order to clarify if such rigid rotation is common, or galaxies have similar rotation curves to the Milky Way, we have performed high-resolution CO-line observations. We have also obtained CCD spectroscopy in the Hα and [NII] line emissions of the central regions of galaxies. In deriving rotation curves, we applied the envelop-tracing method from

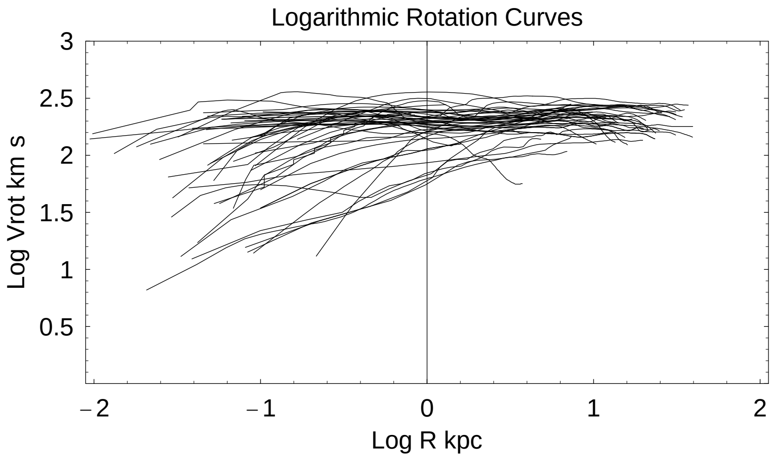

Fig. 1b. The same as Fig. 1a, but in a logarithmic plot.

PV diagrams. In Fig. 1a, we show the most-completely-sampled rotation curves (Papers I - IV).

2.2 Logarithmic Rotation Curves

Since the dynamical structure of a galaxy varies with the radius rapidly toward the center, a logarithm plot would help to overview the innermost kinematics. In fact, logarithmic plots in Fig. 1b demonstrate the convenience to discuss the central kinematics. In such a plot, we may argue that high-mass galaxies show almost constant rotation velocities from the center to outer edge.

2.3 Universal Properties

We may summarize that the universal properties of rotation curves in Fig. 1 and 2 as follows, which are similar to those for the Milky Way.

(1) Steep central rise and peak, often starting from high velocity at the nucleus;
(2) Bulge component, often causing the central peak of rotation curve;
(3) Broad maximum by the disk; and
(4) Halo component.

The steep nuclear rise of rotation is a universal property for massive Sb and Sc galaxies, regardless the morphological peculiarities, while less massive galaxies tend to show a rigid-body rise. The fact that almost all massive galaxies show the steep rise indicates that it is not due to non-circular motion by chance. Even if there is a bar, we have more chance to observe shocked gas bound to the potential than high-velocity flows: We have more chance to observe the pattern speed than the high-velocity flow, which would result in underestimating the true rotation velocity.

3 Mass-to-Luminosity Ratio and the Dark Mass Fraction (DMF)

Once an accurate rotation curve from the center to the outer edge is obtained, we can directly calculate the surface mass density. One extreme case is to assume a spherical symmetry: the rotation velocity is used to calculate the total mass involved within a radius, which is then used to calculate the surface mass density. Another extreme case is to assume a thin disk: the surface mass density can be directly calculated by using the Poisson equation (e.g. Binney and Tremaine 1987). We may safely assume that the true mass distribution lies in between these two cases. We have, thus, calculated the mass distribution for the galaxies for which accurate rotation curves have been obtained. Results for spherical and disk assumptions are found to be coincident usually within a factor of 1.5 to 2. We stress that this method is not intervened by any potential models, as widely adopted in such a method to fit calculated rotation curves by assuming potentials (Kent 1987).

The surface mass density can be, then, directly compared with observed surface luminosity, from which we can derive the mass-to-luminosity ratio (M/L) Fig. 2 shows the thus obtained radial distributions of M/L for a disk assumption (Takamiya and Sofue 1999). The figure indicates that the M/L is not constant at all, but varies significantly within a galaxy. Since the M/L of stars will not vary so drastically, this diagram can be interpreted to represent the distribution of the dark mass fraction (DMF) for the first approximation, namely the minimal DMF.

(1) M/L and DMF vary drastically within the central bulge. In some galaxies, it increases inward toward the center, suggesting a dark massive

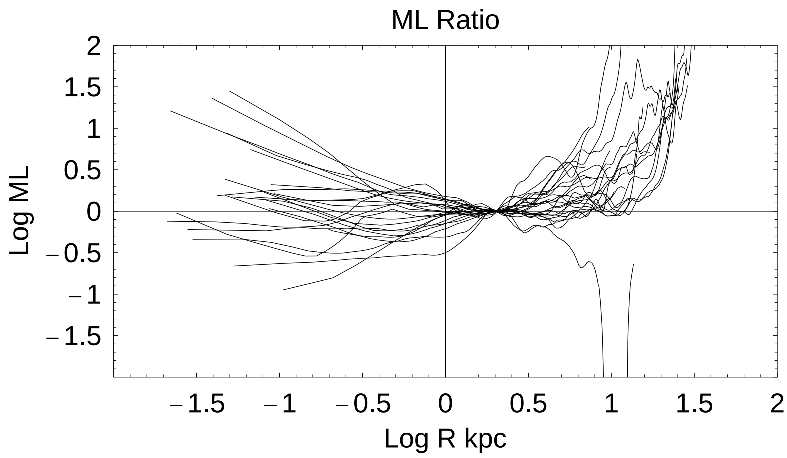

Fig. 2. Radial variation of M/L ratio, as normalized to unity at radius 2 kpc. M/L is not constant at all, but varies within the bulge and disk, and steeply increases toward the halo.

core. In some galaxies, it decreases toward the center, likely due to luminosity excess such as due to active nuclei.

(2) M/L and DMF gradually increases from the inner disk to outer disk, and the gradient increases with the radius.

(3) M/L and DMF increases drastically from the outer disk toward the outer edge, indicating the massive dark halo. In many galaxies, the dark halo can be nearly directly seen from this figure, where the M/L exceed ten, and sometimes hundred.

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