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Central Rotation Curves of Galaxies

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Abstract. We emphasize the use of high-resolution CO line observations to derive central rotation curves of galaxies. We present an example for high-resolution interferometer observations of NGC 3079, and discuss the position-velocity (PV) diagram and derived rotation curve (RC). The CO central rotation curves are combined with the outer curves from Hα and H I-line observations to obtain total RC. We show that well resolved RCs for massive galaxies generally start from non-zero velocities at the nucleus.

1. Introduction

The CO molecular lines are useful to derive accurate rotation curves in the central regions of spiral galaxies, because of the high concentration in the center as well as for negligible extinction (Sofue 1996; Sofue et al. 1997, 1998, 1999). Recent high-dynamic-range CCD spectroscopy in optical lines also make it possible to obtain high accuracy rotation curves in the central regions (Rubin et al. 1997; Bertola et al. 1998). However, in general, optical lines suffer from significant extinction by the central dusty disks, which is particularly significant for highly-inclined and edge-on galaxies. Hence, the CO lines will be the most appropriate tool to investigate the central kinematics of spiral galaxies, if the angular resolution is sufficiently high. In this paper, we present recent high-resolution interferometer observations of CO lines, and discuss the general properties of central rotation kinematics based on the high-accuracy rotation curves.

2. High-Resolution CO Observations of NGC 3079

In order to see if the central steep rise, or more likely non-zero start of the velocity, is indeed the case at higher resolutions than the current observations, we have performed interferometer observations at Nobeyama in the CO$(1-0)$ line of nearby CO-rich galaxies. Here, we present an example for the edge-on galaxy NGC 3079, which exhibits a very dense central molecular core with various nuclear activities (Sofue et al. 2001). The ^{12}CO$(1-0)$ observations of NGC 3079 were made in January to April 2000 using the 7-element mm-wave interferometer at Nobeyama, which consisted of the 6-element mm-wave array in A configuration linked with the 45-m telescope. We also obtained C and D-

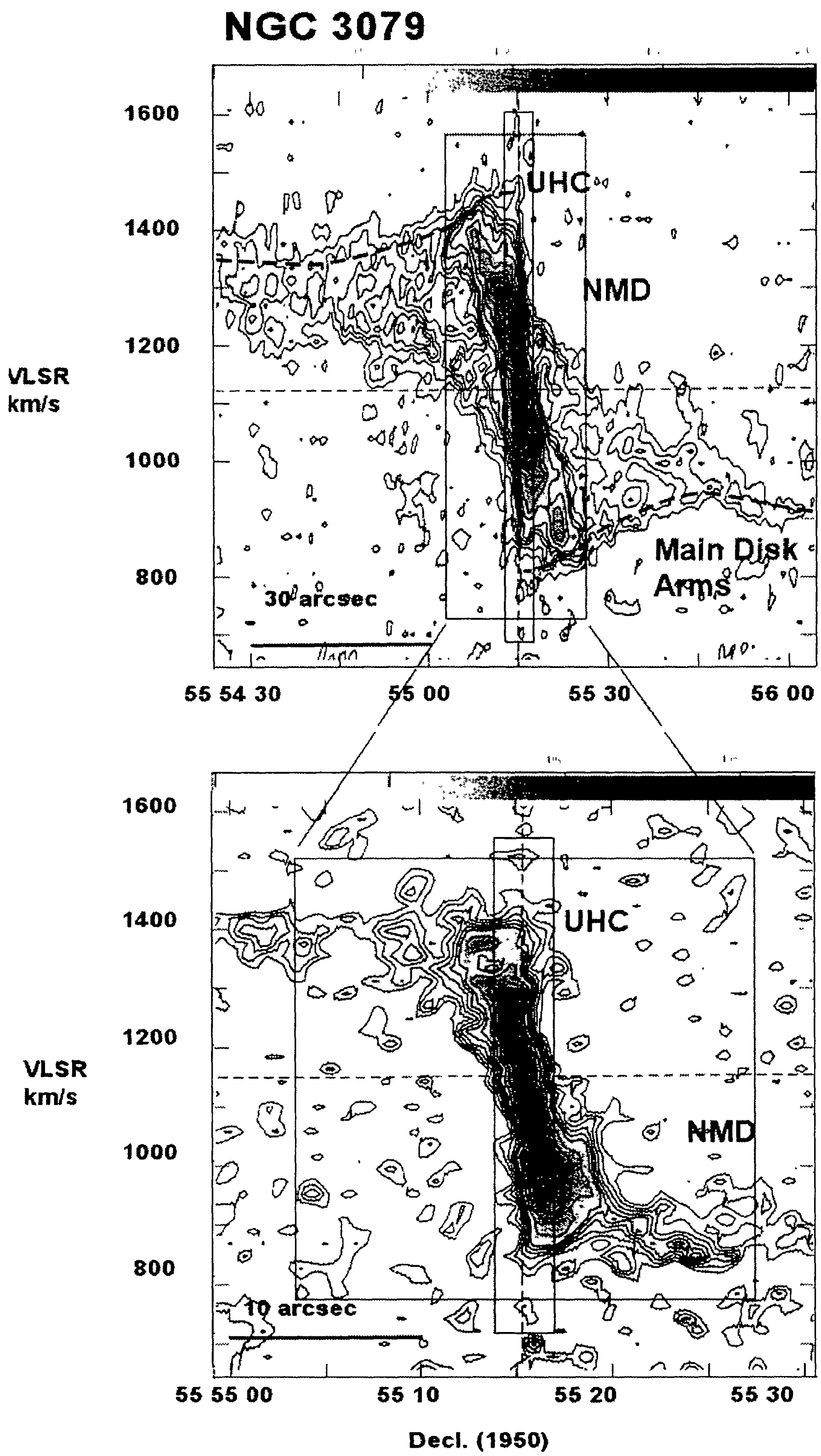

Figure 1. Position-velocity diagram along the major axis of NGC 3079 in CO(1 – 0) line at resolutions of 1."6 × 1."4 (upper panel) and 1."2 × 1."1 (lower panel). Note that the rotation velocity does not decline to zero at the nucleus, but remains always at finite value. UHC stands for ultra-high-density molecular core, and NMD for nuclear molecular disk. 1″ corresponds to 75 pc.

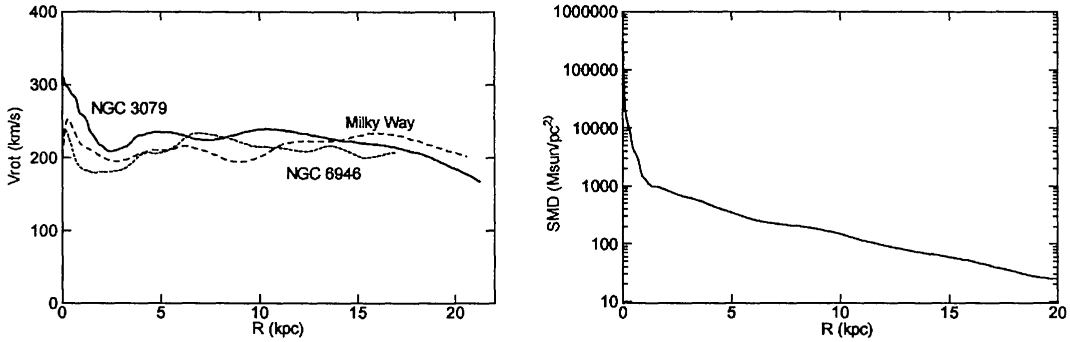

Figure 2. Left panel: Rotation curve of NGC 3079, compared with that of the Milky Way and NGC 6946. Right panel: Surface mass density distribution in NGC 3079.

compact array observations, and all PV data were combined. Fig. 1 shows the obtained PV diagrams.

The CO line intensity distribution in NGC 3079 is summarized as follows: (a) An ultra-high-density compact and massive molecular core (UHC) of radius 125 pc and molecular mass of $3 \cdot 10^8$ $M_\odot$ is detected at the nucleus. (b) The core is embedded in a warped nuclear molecular disk (NMD) of radius 900 pc, and the disk has two spiral arms. (c) An outer disk extending for more than 2 kpc along the major axis.

3. Position-Velocity Diagrams and Rotation Curve

Fig. 1 shows the obtained PV diagrams for the central regions of NGC 3079, where the central UHC and NMD are resolved out both in the velocity and space. The UHC shows up as an intense PV ridge near the center. The rotation velocity of the molecular core increases toward the nucleus, and the velocity does not decline to zero at the center, indicating that the rotation curve starts from a finite value already at the center with at about 300 km s^{-1} or greater. The warped nuclear disk shows up as an inclined ridge in the PV diagram, representing two-armed spiral arms. The radius of this disk component is $\pm 12''$, or the total radius is about ± 900 pc. The main disk of the galaxy in the PV diagram shows up as two fainter ridges with smaller relative velocities, bifurcating from the main ridge of the nuclear disk. These bifurcated ridges show roughly rigid rotation, but at slower velocities, which represents foreground/background spiral arms. We also notice a velocity displacement between the two arm-like features, which may represent non-circular motion driven by the spiral density waves.

Using the PV diagram, we derived a central rotation curve, and combined it with the existing data (e.g. those from Irwin & Seaquest 1991) to obtain total rotation curve as shown in Fig. 2. The rotation velocity starts from a finite value of about 300 km s^{-1}, and declines to a first minimum of about 200 km s^{-1} at $30''$ (2.5 kpc) radius. It is then followed by a broad disk maximum of $V \sim 240$ km s^{-1} at 5 to 10 kpc, and then by a declining outermost rotation.

Using the rotation curve, we can derive a differential surface mass density as a function of radius by applying the method developed by Takamiya & Sofue

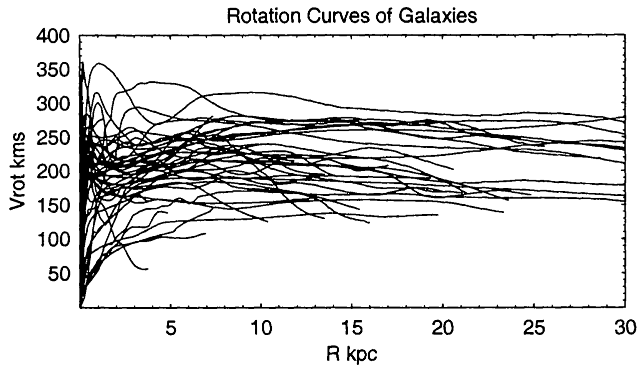

Figure 3. High-accuracy rotation curves of Sb, Sc, SBb and SBc galaxies.

(1999). The surface mass densitu (SMD) increases steeply toward the center, indicating high density cores with SMD> 10^5 $M_\odot$ pc^{-2}. Since NGC 3079 is an Sc galaxy with a poor central bulge, the high mass density could infer a concentration of invisible (dark) mass in the central region.

4. Universal Properties of Rotation Curves

In Fig. 3 we reproduce well-sampled rotation curves obtained by combining CO, CCD Hα, and H I observations from our current study (Sofue et al. 1999). From Figs. 2 and 3, particularly from the case for the highest-quality rotation curves for NGC 3079, we may summarize the universal properties of rotation curves as follows: (1) Massive galaxies generally show very steep rise of rotation in the central region. Mostly likely, the rotation velocity starts from a finite value at the center, indicating a massive core at the nucleus. (2) Small-mass galaxies with slower rotation velocities, however, tend to show more gentle rise. (3) The central rotation is followed by a central peak and/or shoulder corresponding to the bulge. (3) RC is then followed by a road maximum in the disk. (4) The outer RC is flat, and sometimes declining toward the edge.

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