Iteration Method to Derive Exact Rotation Curves from Position-Velocity Diagrams of Spiral Galaxies

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ABSTRACT

We present an iteration method to derive exact rotation curves (RC) of spiral galaxies from observed position-velocity diagrams (PVD), which comprises the following procedure. An initial rotation curve, RC0, is adopted from an observed PV diagram (PV0), obtained by any simple method such as the peak-intensity method. Using this rotation curve and an observed radial distribution of intensity (emissivity), we construct a simulated PV diagram (PV1). The difference between a rotation curve obtained from this PV1 and the original RC (e.g., difference between peak-intensity velocities) is used to correct the initial RC to obtain a corrected rotation curve, RC1. This RC1 is used to calculate another PVD (PV2) using the observed intensity distribution, and to obtain the second iterated RC (RC2). This iteration is repeated until PV_i converges to PV0, so that the differences between PV_i and PV0 becomes minimum. Finally RC_i is adopted as the most reliable rotation curve. We apply this method to some observed PVDs of nearby galaxies, and show that the iteration successfully converges to give reliable rotation curves. We show that the method is powerful to detect central massive objects.

Subject headings: methods: data analysis — ISM: kinematics and dynamics — galaxies: ISM — galaxies: kinematics and dynamics — galaxies: nuclei — galaxies: structure —
1. Introduction

Rotation curves (RC) are one of the most basic informations of dynamics of galaxies (Sofue and Rubin 2001). RCs are used to discuss supermassive black holes (e.g., Dressler & Richstone 1988, Kormendy & Richstone 1992, Bower et al. 1998), the dark matter distribution in the halo (e.g., Rubin et al. 1985, Kent 1986, Persic et al. 1996, Honma & Sofue 1997, Takamiya & Sofue 2000), the characteristics of a bulge and disk (e.g., Kormendy & Illingworth 1982, Kent 1986, Héraudeau & Simien 1997), and kinematic peculiarities (e.g., Márquez & Moles 1996, Barton et al. 1999, Rubin et al. 1999).

RCs of disk galaxies are usually derived from position-velocity diagrams (PVD) by optical (Hα, [NII]) and radio (CO, H2) line observations (SR2001). There have been several ways to derive RCs. Widely used methods are to trace intensity-weighted velocities (Warner et al. 1973), and to trace peak-flux ridges in PVD (e.g., Rubin et al. 1985, Mathewson et al. 1992). These methods give good results for nearly face-on galaxies with sufficiently high spatial resolutions. Other methods are the terminal-velocity method used for our Galaxy (e.g., Clemens 1985), and the envelope-tracing method (Sofue 1996), which traces the envelope velocities on PVD and correct for the intrinsic interstellar velocity dispersion and resolutions to estimate terminal velocities. This method gives better results for the central regions and for highly inclined and edge-on galaxies (Olling 1996). Sofue (1996) applied this method also to intermediate inclined galaxies to obtain central-to-outer RCs of many spiral galaxies.

The envelope-tracing method would be the most practical way to derive RCs in disk galaxies. However, it still has difficulties to derive exact velocities in the central regions because of very high apparent velocity widths due to unresolved rapidly-rotating components, whose radial and tangential points are observed in a finite beam, due to steep velocity gradients, and complex gas distribution.

In this paper, we first analyze the observational conditions under which the peak-traced velocity does not accurately follow the true rotation velocity by simulating PV diagrams using model RCs. Next, we propose a new iteration method to derive a RC, and apply it to some observations and compare with the peak-flux and envelope-tracing methods. We finally stress the advantage to use the iteration method to the search for central massive cores and black holes.

2. PVD Simulation

Given a RC, the shape of a PV diagram depends on the observational parameters such as the seeing size, slit width, or equivalently the beam size, and spectral resolution. The PV shape also depends on the intrinsic parameters of the galaxy itself such as the inclination of the disk, interstellar velocity dispersion, and the gas distribution. In order to see how these parameters affect the observed PVDs, we simulate PVDs from a given RC for a model galaxy, and show the result in figure 1. Observational parameters such as the assumed slit width, velocity resolution and seeing size are given on the top of the figure.

The model galaxy is put at a distance of 10 Mpc (1″=49pc). The galaxy is assumed to have a similar RC to that of the Milky Way expressed by a Miyamoto-Nagai potential model (Miyamoto & Nagai 1975) with a massive central core, bulge, disk and dark halo, as shown by the thick line in the upper panel. The gas disk has an exponential density profile as indicated by the thin line in the lower panel, which is expressed by

\[ \rho \propto \exp \left( -\frac{r}{h_r} - \frac{|z|}{h_z} \right), \]

where \( r \), \( h_r \), and \( h_z \) are the radius, height from the galactic plane, the scale radius, and the scale height. We assume that \( h_r = 1.5 (\text{kpc}) \) and \( h_z = 60 (\text{pc}) \), and the inclination to be 80°. The interstellar velocity dispersion of the order of 5 to 10 km s\(^{-1}\) is assumed to be sufficiently small compared to the observational velocity resolution, which is taken to be 35 km s\(^{-1}\).

The middle panel of figure 1 shows the ratio of the 'observed' peak-intensity velocity in the simulated PVD to the assumed rotation velocity. The simulated PVD behaves rigid-body like in the central regions, and hence, if we use peak-intensity velocities, the rotation velocity is significantly underestimated. We also made the simulation for various parameter sets, and found that the larger is the inclination, the more is the underestimation, because we observe more amount of foreground and background disk gases on the line-of-sight with nearly zero radial velocities for higher inclination galaxies.

Moreover, if the central region is gas deficient, namely if the gas distribution is ring like, the ob-
served PV diagram behaves more rigid-body like, even if the assumed central rotation velocity was extremely high. Underestimation of central rotation velocities was found in all of cases, and it amounted to 50% to 100% of the intrinsic rotation velocities. The underestimation were found even for the envelope-tracing method, although it gave better results than the peak-tracing method. Hence, the current widely used methods may not be appropriate to discuss rotation curves and related properties such as the mass distribution in the central regions of spiral galaxies.

3. Iteration Method

In order to derive more reliable RCs from observed PV diagrams, particularly for the central regions of spiral galaxies, we propose a new method, which comprises the following algorithm, which we call hereafter the iteration method. Figure 2 shows the flow-chart of this algorithm.

— Fig. 2 —

1. We define a radial velocity profile traced at 20%-level envelope of the peak flux in a PV diagram as a comparison velocity, and take this profile as the initial trial RC, $V_{ini}(r)$.

2. At each radius we calculate velocity-integrated intensity using the observed spectrum, or equivalently by integrating the PV diagram in the direction of velocity at a fixed radius. We assume that the integrated intensity is proportional to the column density of interstellar gas along the line of sight, $\Sigma(r)$. The gas density distribution, $\rho(r, z)$, in the galaxy is assumed to have a disk form with an exponential $z$ directional structure:

$$\rho(r, z) = A \Sigma(r) \times \exp\left(-\frac{|z|}{h_z}\right). \quad (2)$$

Here, $h_z$ is the scale height of the disk, and assumed to be constant at 60 pc for all galaxies. The constant coefficient $A$ is taken to be arbitrary, because the absolute values of PV intensities do not affect the resultant rotation velocities in the present method. The thus once calculated $\rho(r, z)$ is used through the entire iteration process.

3. Based on $V_{ini}(r)$ and $\rho(r, z)$, a PV-diagram is calculated using observational parameters such as the slit width, velocity resolution, and seeing size (beam size), which are taken to mimic the real observations. We use this new PV diagram to derive a new 20%-level envelope of the peak flux, and obtain a new RC with velocities $V_{com}$.

4. We define the difference between the first trial RC and this calculated RC by $\delta V = V_{ini} - V_{com}$, and use it to correct for $V_{ini}$ to obtain the second iterated RC, $V_2 = V_{ini} + \delta V$.

5. We calculate another PV diagram using $V_2$ and obtain the second iterated RC, $V_{com,2}$, which is then compared with $V_{ini}$ to calculate $\delta V_2 = V_{ini} - V_{com,2}$, and obtain $V_3 = V_2 + \delta V_2$.

6. We repeat this procedure for $i$ times to obtain the $i$-th iterated RC, $V_i = V_{i-1} + \delta V_i$, until $\delta V_i$ becomes smaller than a criterion, e.g. until $|\delta V_i|$ becomes sufficiently small compared to the velocity resolution. Here, $V_{com,i}$ converges to $V_{ini}$ within the error, and the calculated RC becomes approximately identical to the observed RC within the rms noise. Finally, we adopt $V_i$ as the most reliable rotation curve.

Here, we used the original $\Sigma$ obtained from observation to calculate the iterated PVDs, whereas we used corrected velocities. In order to obtain fully consistent iteration, the surface density must also be replaced by corrected ones. However, this would make the program very sophisticated, and will be a subject for the future. We only mention that the correction for $\Sigma$ would be much less effective compared to the correction to velocities, because the gas distribution is not expected to change so drastically compared to velocities, which may have an extremely steep rise near the nucleus.

4. Application to Observational Data

We applied the iteration method to optical spectral data obtained by using the 1.88-m telescope at Okayama Astrophysical Observatory (Sofue et al. 1998), and to the CO ($J = 1 - 0$) line data observed with the Nobeyama mm-wave Array (NMA) (Sofue et al. 2001; Koda et al. 2002; Sofue et al. in preparation). Here, we display some examples of the results applied to NMA CO-line observations.

Figure 3a (left panel) shows an original PVD for the edge-on Sc galaxy NGC 3079 in the CO line emission, exhibiting a central high-velocity rotating molecular disk. Figure 3b (middle) shows the obtained rotation curve by applying the iteration method, and a constructed PVD by convining this RC with the observed intensity profile. In figure 3c (right), we show a simple rotation curve obtained by the peak-tracing method, which corresponds to the initial trial RC in figure 2, and a convoluted PVD. The iteration
method gives an extremely steep rotation curve, and reproduces the observed PVD very well. On the other hand, the peak-tracing method gives a mild rotation curve, but the reconstructed PVD cannot reproduce the observation.

Figures 3d to 3f are the same, but applied to a mildly inclined Sb galaxy NGC 4536. Again, we find the iteration method gives a reasonable reproduction of the observed PVD, while the other method cannot reproduce the observation. In both cases, peak-intensity velocities lead to underestimated rotation velocities by 50 to 100 km s\(^{-1}\) in the central regions. In figure 4 we show some more examples of rotation curves obtained by the iteration method superposed on the original PVDs. Very steeply rising rotation curves are obtained for most cases.

— Fig. 3, 4 —

5. Discussion

The iteration method has some advantage to the current methods, and will be particularly powerful to determine the central rotation curves, and therefore, to detect massive central objects. In fact most of the galaxies shown in figures 3 and 4 have very high velocities near the centers, which suggest the existence of massive cores around the nuclei. Underestimation of RCs in the central region significantly affects the discussion of the central structure (Takamiya and Sofue 2000).

The iteration method uses all data points to reproduce the observed PVDs by simulating the observed PVD, and hence, the statistical error in the results are smaller compared to other methods. For example, the peak-tracing and envelope-tracing methods uses only a part of each velocity profile. Hence, the amount of data available to fit observation is by a factor of ten greater in the present method than the current method. The intensity-weighted velocity method uses all data, but smears out the detailed velocity information, and the result is approximately the same as that from the peak-tracing method, which also significantly underestimate the central velocities.

Finally, we stress that the present method does not need any potential model, and therefore, the result is purely observational and unique. This unique rotation curve can be further used to calculate the mass distribution directly by a deconvolution technique as described in Takamiya and Sofue (2000). A method comparing the shapes of observed and calculated PV diagrams has been used by Bertola et al. (1998) to detect central massive objects. They assumed a central potential model in order to mimic the PV diagrams, and hence, the method cannot measure the error quantitatively, and the mass model may not necessarily be unique. Application of the iteration technique to these current observations would also give more reliable answer to the existence of such massive objects.

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Figure Captions

Fig. 1. [Upper panel] Simulated PV diagram from an assumed rotation curve (thick line). [Lower panel] Gas density distribution used for constructing the PV diagram. [Middle panel] Difference of the peak-traced velocity in the PVD from the original rotation curve.

Fig. 2. Flow chart of the algorithm of the iteration method to derive a rotation curve from the observed PVD.

Fig. 3. (a) (left panel) Observed PVD of the edge-on galaxy NGC 3079. (b) (middle) Rotation curve obtained by the iteration method and the resultant PVD. (c) (right panel) Peak-traced rotation velocity and corresponding PVD. (d) to (f) Same as (a) to (c), but for the Sb galaxy NGC 4536.

Fig. 4. Examples of rotation curves obtained by the iteration method superposed on the high-resolution CO-line PVDs obtained by the Nobeyama mm-wave Array (Sofue et al. in preparation).
Observed PV Dia.

$V_{ini}(r)=V(20\%)$ or $V_{peak}$

Initial: $V_1=V_{ini}$

Intensity distrib.:
Surf. density ($r$)

PVD $i$

$V_{com}(r)=V(20\%)$ or $V_{peak}$

$V_{com}: dV_i=V_{ini} - V_{com}$

$V_{output}(r)=V_i(r)$ Rotation Curve

$V_i+1=V_i+dV_i$

$|dV_i|<\text{Criterion?}$

No

Yes

Rotation Curve
