A new method for determining mass-to-light ratios of nearly face-on spiral galaxies

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ABSTRACT

Aims. This letter gives a new method for determining mass-to-light ratios of nearly face-on spiral galaxies.

Methods. The method is based on the effective thickness of the galactic disk, the distribution of the vertical velocity dispersion, and the surface brightness of a spiral galaxy.

Results. As examples, the results of the determination of NGC 1566 and NGC 5247 in B-band are presented, and their mass-to-light ratios are 4.86 ~ 8.99 M⊙ L⊙⁻¹ and 5.02 ~ 6.90 M⊙ L⊙⁻¹ respective.

Key words. galaxy: disk – galaxies: fundamental parameters – galaxies: spiral – galaxies: structure – galaxies: individual: NGC 1566, NGC 5247

1. Introduction

Van der Kruit & Searle (1981a,b) investigated surface photometry of edge-on spiral galaxies, they fitted the z distribution of light at each r of the disk by a model of a locally isothermal sheet. Let Φ denote the gravitational force in the z-direction as a function of z, ρ the space density of matter and ⟨Vz²⟩/2 the dispersion in the velocities in the z-direction. From the case Poisson’s and Liouville’s equations, it could be reduced to

\[ \frac{\partial \Phi}{\partial z} = -4\pi G \rho \langle V_z \rangle \]

(1)

\[ \frac{\partial \rho}{\partial z} = \frac{\rho V_z}{\langle V_z^2 \rangle} \]

(2)

with ⟨Vz²⟩/2 independent of z-direction, and the solution is (Camm 1950; Spitzer 1942)

\[ \rho(r, z) = \rho(r, 0) \text{sech}^2 \left( \frac{z}{z_0} \right) \]

(3)

with

\[ z_0 = \frac{\langle V_z^2 \rangle}{2\pi G \rho(r, 0)} \]

(4)

z0 is effective thickness of a galactic disk (H = z0/2 is scale height of a galactic disk).

By integrating Eq. (3), we have the total surface density of disk

\[ \sigma(r) = \frac{0.462 \times \sqrt{x^2 + y^2}}{(\pi G)^{1/2}}, \]

so Eq. (4) can be reduced to

\[ z_0 = \frac{0.462\langle V_z^2 \rangle}{\pi G \sigma(r)} \]

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(6)

Van der Kruit & Freeman (1986) pointed out that the mass-to-light ratio (γ = M/L) of old disk is approximately constant, in good approximation independent of position along the radius. When a spiral galaxy is nearly face-on, the total surface density can be taken as

\[ \sigma(r) = \gamma I(r) = \gamma I_0 e^{-r/r_d}, \]

(7)

with I(r) the surface brightness and r_d the scale length of galactic disk. Therefore, from Eqs. (6) and (7), we can find

\[ \gamma = \frac{0.462\langle V_z^2 \rangle}{\pi G z_0 I_0 e^{-r/r_d}}, \]

(8)

if we obtain the parameters z_0, V_z, I_0, and r_d, mass-to-light ratio γ could be calculated by Eq. (8).
2. Model and data reduction

2.1. The effective thickness $z_0$

Van der Kruit & Searle (1981a) proposed a method to determine the scale heights of edge-on disk galaxies. It is based on measuring surface brightness that is distributed with exponential function of radius. A method for determining the scale heights of spiral galaxies observed non-edge-on was proposed by Peng (1988) on the basis of the asymptotic expression of the perturbed gravitational potential. Zhao et al. (2004) re-investigate the method based on the rigorous expression of the perturbed gravitational potential. We have already obtained perturbed gravitational potential for such a logarithmic density disturbance via the Poisson’s equation for the galactic disk with finite thickness (Peng et al. 1978, 1979), the perturbed gravitational potential may be expressed

$$V_o(r, \phi, z = 0, t) = -2\pi GA \exp[i(\omega t - m\phi + \Lambda \ln r)] \cdot \text{Re}[g(\Lambda, m; ar)],$$

(9)

where

$$g(\Lambda, m; ar) = \exp(i\Lambda \ln 2) \left[ \frac{\Gamma(\frac{m+1}{2})}{\Gamma(\frac{m}{2})} \right] \cdot \int_0^\infty J_m(x) \frac{\exp(-i\Lambda \ln x)}{x(1 + \frac{x}{\alpha})} \text{d}x,$$

(10)

here, $\alpha$ is thickness factor of a spiral galactic disk, $\Gamma(x)$ and $J_m(x)$ are the usual Gamma and Bessel functions, respectively. For an infinitely thin disk ($\alpha \to +\infty$), the Eq. (9) has a simplified form as same as the expression given by Kalnajs (1971)

$$V_o(r, \phi, z = 0, t) = -2\pi GA \exp[i(\omega t - m\phi + \Lambda \ln r)] \cdot \frac{1}{\sqrt{vm^2 + \Lambda^2}}.$$  

(11)

The ratio ($\eta$) of the amplitude for the perturbed gravitational potential for a disk galaxy with finite thickness to that of an infinitely thin disk at the forbidden radius $r_0$ is (Zhao et al. 2004)

$$\eta = \frac{V_o(\alpha, m, \Lambda, r_0)}{V_o(\alpha, m, \Lambda, r_0)} = \text{Re}[g(\Lambda, m; ar_0)] \cdot \frac{1}{\sqrt{vm^2 + \Lambda^2}},$$

(12)

it can be obtained the effective thickness ($z_0 = 2/\alpha$) through Eq. (12) by determining the winding parameter ($\Lambda$), the number of spiral arms ($m$), and the forbidden radius ($\Lambda$ spiral arm can not extend to the forbidden region with radius $r_0$ to the galactic center). $\eta$ was assumed to be 0.5 based on the comparison between $z_0$ and $r_0$ which have been observed and measured for Milky Way and Andromeda Nebula (M 31). In fact, we use the same values of the parameters of 71 spiral galaxies given by Ma et al. (1998) to calculate the factor $\eta$ by Eq. (12), and obtain the average $\eta \approx 0.486$. In this paper, we take the average value of $0.5$ and $0.486$, i.e., $\eta = 0.493$.

It is well known that spiral arms can be represented by equiangular spirals on the galactic disk. In Fig. 1, we determine the inclinations and the winding parameters of the spiral galaxies NGC 1566 and NGC 5247 ($B$-band) by fitting the curves of spiral arms in their images, i.e., it is the optimum inclination of a spiral galaxy, which is corresponding to the best fitted spiral curves.

2.2. $V_z$ and surface brightness of NGC 1566 and NGC 5247

NGC 1566 and NGC 5247 were investigated based on studying the surface photometric and spectroscopic by Bottema (1992) and Van der Kruit & Freeman (1986), respectively. The parameters $V_z$, $I_0$, and $r_d$ we need are listed in Table 1 in this paper. As shown in Table 1 Col. 5, the vertical velocity dispersion $V_z$ of NGC 1566 was obtained from Table 4 Col. 4 in Bottema’s paper (1992) and NGC 5247 from Table 1 Col. 4 in Van der Kruit & Freeman (1986), it only needs to get $V_{zr}$ at the radius $r$ in the galactic disk. However, we have obtained the effective thickness $z_0$, the vertical velocity dispersion $V_z$, and the surface brightness $I(r)$ at radius $r$, the only unknown parameter is mass-to-light ratio $\gamma$ in Eq. (8).

3. Results

On the basis of the method proposed in this paper, we obtain the effective thicknesses ($z_0$) of NGC 1566 and NGC 5247 by Eq. (12) and their mass-to-light ratios ($\gamma$) by Eq. (8). The main results are listed in Table 2, $\gamma$ listed in Col. 8 and $z_0$ in Col. 7.

4. Discussion

1. As shown in Fig. 2 with four panels (Figs. 2a–d), Fig. 2a is displayed the radial dependence of $V_V = V_o/V_o(\infty)$ by Eqs. (9) and (11), it is noted that $V_V$ is the ratio for the amplitude of the gravitational potential perturbation of a disk with finite thickness to that of an infinitely thin disk. As an example, we choose a sample with two spiral arms and winding parameter $\Lambda = 12.0$. The curves from the top to bottom denote the galactic disk with different effective thicknesses correspond to $z_{01}$ = 0.20 kpc ($\alpha_{01}$ = 10.00 kpc$^{-1}$), $z_{02}$ = 0.50 kpc ($\alpha_{02}$ = 4.00 kpc$^{-1}$), and $z_{03}$ = 1.00 kpc ($\alpha_{03}$ = 2.00 kpc$^{-1}$), respectively. In
The effective thicknesses and the mass-to-light ratios of NGC 1566 and NGC 5247 (B-band).

<table>
<thead>
<tr>
<th>NGC</th>
<th>m</th>
<th>φ</th>
<th>r₀</th>
<th>Λ</th>
<th>α</th>
<th>z₀</th>
<th>γ</th>
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<td></td>
<td>(°)</td>
<td>(kpc)</td>
<td>(kpc⁻¹)</td>
<td>(kpc)</td>
<td>(M_☉ L_☉⁻¹)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1566</td>
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<td>23.0</td>
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<td>13.072</td>
<td>0.153</td>
<td>5.02</td>
</tr>
<tr>
<td>5247</td>
<td>22</td>
<td>3.23</td>
<td>6.82</td>
<td>7.018</td>
<td>0.285</td>
<td>4.86</td>
<td>8.99</td>
</tr>
</tbody>
</table>

* Column 2: m is the number of spiral arms.
* Column 3: φ is the optimum inclination of the galactic disk.
* Column 4: r₀ is the forbidden radius.
* Column 5: Λ is the winding parameter of spiral arms, and pitch angle μ = arctan(m/Λ).
* Column 6: α is the thickness factor, α = 2/ζ₀.
* Column 7: ζ₀ is the effective thickness of the galactic disk, and here, errors (∆ζ₀) of ζ₀ are ∆ζ₀(NGC 1566) = 20.3% and ∆ζ₀(NGC 5247) = 18.1%.

Fig. 2. Panel a) shows \( V_\text{ Expense} = V_\text{ Expense}/V_\text{ Expense} \) with different ζ₀ (ζ₀ = 2/α). \( V_\text{ Expense} \) is the ratio for the amplitude of the gravitational potential perturbation of a disk with finite thickness to that of an infinitely thin disk. The curves from top down correspond to ζ₀₁ = 0.20 kpc (α₀₁ = 10.00 kpc⁻¹), ζ₀₂ = 0.50 kpc (α₀₂ = 4.00 kpc⁻¹), and ζ₀₃ = 1.00 kpc (α₀₃ = 2.00 kpc⁻¹), respectively. Panels b)-d) are three panels for NGC 1566 to illustrate the changes of ζ₀ with r₀, Λ, and m, respectively.

Fig. 2a, it is shown that the amplitude of gravitational perturbation for a disk with finite thickness is weaker than that of an infinitely thin disk, and the thicker the galactic disk is, the weaker the amplitude of the gravitational potential perturbation becomes. When it is close to the center of the disk (r → 0), the decrease of the amplitude of gravitational potential perturbation becomes even faster, the amplitude is too weak to stir up the self-consistent density waves due to the physical concept of density waves suggested by Lindblad, spiral arms would disappear in the forbidden region with radius r₀ to the galactic center. When \( V_\text{ Expense} = η = 0.493 \) as shown in Fig. 2a, the thicker the galactic disk is, the larger the forbidden radius becomes (r₀₃ > r₀₂ > r₀₁).

2. Figures 2b–d are three panels for NGC 1566. ζ₀ is obtained by calculating Eq. (12). Figure 2b shows the effective thickness ζ₀ changes with r₀, keeping the other two parameters m and Λ constant at their adopted values in Table 2. We could note that ζ₀ becomes thicker as the the forbidden radius r₀ is increased, it is in agreement with the conclusion obtained from Fig. 2a (where \( V_\text{ Expense} = η = 0.493 \), the thicker the galactic disk is, the larger the forbidden radius r₀ becomes.).

Figure 2c is shown the change of ζ₀ with Λ, keeping m and r₀ constant. We can learn from Peng (1988) and Ma et al. (1998) that ζ₀ \( < r_0 Λ^{-1} \), for the spiral galaxies with the same or similar value of ζ₀, the forbidden radii r₀ become larger as Λ be increased, it shows some correlations with Hubble sequence. As displayed in Fig. 2c, r₀ is kept constant at the value in Table 2, ζ₀ becomes thinner as Λ becomes larger, it is in agreement with the method for determining the thickness of a spiral galactic disk by Peng (1988) and Ma et al. (1998).

Figure 2d shows the dependence of ζ₀ on the parameter m, keeping r₀ and Λ constant. It is noted that the larger the number of spiral arms (m) becomes, the narrower the gap of the spiral arms is. It is similar to the result of Λ increased, when Λ is increased, the gap of the spiral arms becomes smaller. As shown in Fig. 2d, ζ₀ becomes thinner as m becomes larger.

3. The mass-to-light ratios of NGC 1566 and NGC 5247 in B-band given by Bottema (1992) and Van der Kruit & Freeman (1986) respectively are both 5.0 \( \sim 10.0 \) M_☉ L_☉⁻¹. As shown in Table 2 Col. 8 in this paper, we obtain the mass-to-light ratios of NGC 1566 and NGC 5247 are 4.86 \( \sim 8.99 \) M_☉ L_☉⁻¹ and 5.02 \( \sim 6.90 \) M_☉ L_☉⁻¹, respectively.

4. Van de Kruit & Searle (1981a) and de Grijs & Van de Kruit (1996) found that, for scale heights of edge-on spirals, \( H = ζ₀/2 \) is in good approximation independent of position along the major axis, but Kent et al. (1991), de Grijs & Peletier (1997) noted that the scale height seems to increase with radius along the major axis, it seems to occur more often in early type galaxies than in later type. Shaw & Gilmore (1990) found that the radial variation of scale heights is within \( \pm 3\% \), with no dependence on color or model type. Here, we presume scale height to be approximately constant along the axis of the galactic disk, and for Eq. (8), it is obvious that mass-to-light ratio is approximately constant too, in agreement with Van der Kruit & Freeman (1986).

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