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Letter to the Editor

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 $4.86 \sim 8.99\ M_\odot\,L_\odot^{-1}$ and $5.02 \sim 6.90\ M_\odot\,L_\odot^{-1}$ 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_z denote the gravitational force in the z-direction as a function of z, ρ the space density of matter and $\langle V_z^2\rangle^{1/2}$ the dispersion in the velocities in the z-direction. From the case Poisson's and Liouville's equations, it could be reduced to

$$\frac{\partial \Phi_z}{\partial z} = -4\pi G\rho(z) \tag{1}$$

$$\frac{\partial \rho}{\partial z} = \frac{\rho V_z}{\langle V_z^2\rangle}, \tag{2}$$

with $\langle V_z^2\rangle^{1/2}$ independent of z-direction, and the solution is (Camm 1950; Spitzer 1942)

$$\rho(r,z) = \rho(r,0)\mathrm{sech}^2\left(\frac{z}{z_0}\right) \tag{3}$$

with

$$z_0 = \frac{\langle V_z^2\rangle^{1/2}}{[2\pi G\rho(r,0)]^{1/2}}, \tag{4}$$

z_0 is effective thickness of a galactic disk ($H = z_0/2$ is scale height of a galactic disk).

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

$$\sigma(r) = \frac{0.462\times\sqrt{2}\rho(r,0)^{1/2}\langle V_z^2\rangle^{1/2}}{(\pi G)^{1/2}}, \tag{5}$$

so Eq. (4) can be reduced to

$$z_0 = \frac{0.462\langle V_z^2\rangle}{\pi G\sigma(r)}. \tag{6}$$

Van der Kruit & Freeman (1986) pointed out that the mass-to-light ratio ($\gamma = M/L$) 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

$$\sigma(r) = \gamma I(r) = \gamma I_0 \mathrm{e}^{-r/r_\mathrm{d}}, \tag{7}$$

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

$$\gamma = \frac{0.462\langle V_z^2\rangle}{\pi G z_0 I_0 \mathrm{e}^{-r/r_\mathrm{d}}}, \tag{8}$$

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

$$V_\alpha(r,\phi,z=0,t) = -2\pi GA\exp[\mathrm{i}(\omega t - m\phi + \Lambda\ln r)]\cdot \mathrm{Re}[g(\Lambda,m;\alpha r)], \quad (9)$$

where

$$g(\Lambda,m;\alpha r) = \exp(\mathrm{i}\Lambda\ln 2)\frac{\Gamma(\frac{1+m+\mathrm{i}\Lambda}{2})}{\Gamma(\frac{1+m-\mathrm{i}\Lambda}{2})}\cdot \int_0^\infty J_m(x)\frac{\exp(-\mathrm{i}\Lambda\ln x)}{x(1+\frac{x}{\alpha r})}\mathrm{d}x, \quad (10)$$

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

$$V_{\alpha\to+\infty}(r,\phi,z=0,t) = -2\pi GA\exp[\mathrm{i}(\omega t - m\phi + \Lambda\ln r)]\frac{1}{\sqrt{m^2+\Lambda^2}}. \quad (11)$$

The ratio (η) 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)

$$\eta = \frac{V_\alpha(\alpha,m,\Lambda,r_0)}{V_{\alpha\to\infty}(m,\Lambda,r_0)} = \mathrm{Re}[g(\Lambda,m;\alpha r_0)]\sqrt{m^2+\Lambda^2}, \quad (12)$$

it can be obtained the effective thickness ($z_0 = 2/\alpha$) through Eq. (12) by determining the winding parameter (Λ), the number of spiral arms (m), and the forbidden radius (A spiral arm can not extend to the forbidden region with radius r_0 to the galactic center.). η 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 η 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., $\overline{\eta} = 0.493$.

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.

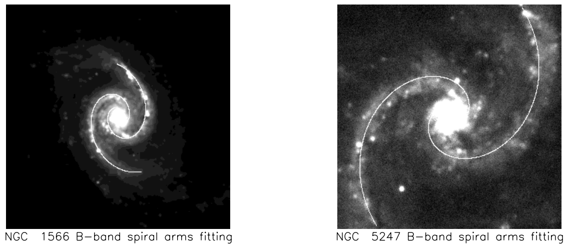

Fig. 1. Images of NGC 1566 and NGC 5247 in *B*-band with superposed fitted curves of spiral arms.

Table 1. V_z and parameters of surface brightness of NGC 1566 and NGC 5247 (*B*-band).

NGC	Band	d (Mpc)	r (kpc)	$V_{z,r}$ (km s^{-1})	I_0 ($L_\odot$ pc^{-2})	r_d (kpc)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
1566	*B*	17.4	2.5 ~ 3.1	60 ~ 40	221	3.0
5247	*B*	16.7	2.4 ~ 3.2	40 ~ 30	225	3.1

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 $V_{z,r}$ at the radius r in the galactic disk. However, we have obtained the effective thickness z_0, the vertical velocity dispersion $V_{z,r}$, and the surface brightness $I(r)$ at radius r, the only unknown parameter is mass-to-light ratio γ 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 (γ) by Eq. (8). The main results are listed in Table 2, γ 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 $V_V = V_\alpha/V_{\alpha\to\infty}$ 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

Table 2. The effective thicknesses and the mass-to-light ratios of NGC 1566 and NGC 5247 (B-band).

NGC	m	ϕ	r_0	Λ	α	z_0	γ
		$(^0)$	(kpc)		(kpc^{-1})	(kpc)	$(M_\odot\, L_\odot^{-1})$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1566	2	32.3	0.996	6.82	7.018	0.285	4.86 ~ 8.99
5247	2	23.0	0.358	4.25	13.072	0.153	5.02 ~ 6.90

* Column 2: m is the number of spiral arms.
* Column 3: ϕ is the optimum inclination of the galactic disk.
* Column 4: r_0 is the forbidden radius.
* Column 5: Λ is the winding parameter of spiral arms, and pitch angle $\mu = \arctan(m/\Lambda)$.
* Column 6: α is the thickness factor, $\alpha = 2/z_0$.
* Column 7: z_0 is the effective thickness of the galactic disk, and here, errors ($\triangle z_0$) of z_0 are $\triangle z_{0(\mathrm{NGC\,1566})} = 20.3\%$ and $\triangle z_{0(\mathrm{NGC\,5247})} = 18.1\%$.

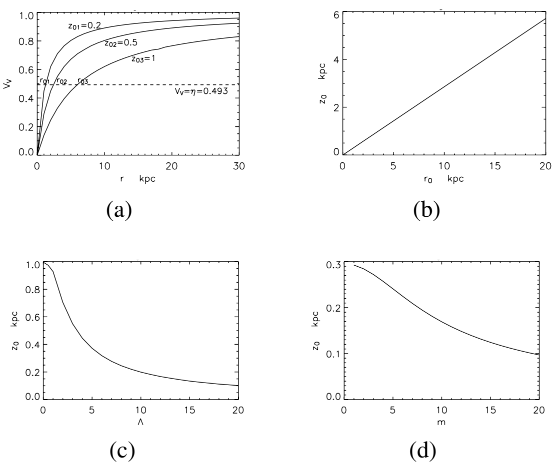

Fig. 2. Panel **a)** shows $V_V = V_\alpha/V_{\alpha\to\infty}$ with different z_0 ($z_0 = 2/\alpha$). V_V is the ratio for the amplitude of the gravitational potential perturbation of a disk with finite thickness to that of an infinitely thin disk. The curves from top down correspond to $z_{01} = 0.20$ 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. Panels **b)–d)** are three panels for NGC 1566 to illustrate the changes of z_0 with r_0, 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 ($r \to 0$), 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 r_0 to the galactic center. When $V_V = \eta = 0.493$ as shown in Fig. 2a, the thicker the galactic disk is, the larger the forbidden radius becomes ($r_{03} > r_{02} > r_{01}$).

2. Figures 2b–d are three panels for NGC 1566. z_0 is obtained by calculating Eq. (12). Figure 2b shows the effective thickness z_0 changes with r_0, keeping the other two parameters m and Λ constant at their adopted values in Table 2. We could note that z_0 becomes thicker as the the forbidden radius r_0 is increased, it is in agreement with the conclusion obtained from Fig. 2a (when $V_V = \eta = 0.493$, the thicker the galactic disk is, the larger the forbidden radius r_0 becomes.).
   Figure 2c is shown the change of z_0 with Λ, keeping m and r_0 constant. We can learn from Peng (1988) and Ma et al. (1998) that $z_0 \propto r_0\Lambda^{-1}$, for the spiral galaxies with the same or similar value of z_0, the forbidden radii r_0 become larger as Λ be increased, it shows some correlations with Hubble sequence. As displayed in Fig. 2c, r_0 is kept constant at the value in Table 2, z_0 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 z_0 on the parameter m, keeping r_0 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, z_0 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 ~ 10.0 $M_\odot\, L_\odot^{-1}$. 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 ~ 8.99 $M_\odot\, L_\odot^{-1}$ and 5.02 ~ 6.90 $M_\odot\, L_\odot^{-1}$, respective.
4. Van de Kruit & Searle (1981a) and de Grijs & Van de Kruit (1996) found that, for scale heights of edge-on spirals, $H = z_0/2$ 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 ±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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References

Bottema, R. 1992, A&A, 257, 69
Camm, G. L. 1950, MNRAS, 110, 305
de Grijs, R., & Van der Kruit, P. C. 1996, A&AS, 117, 19
de Grijs, R., & Peletier, R. F. 1997, A&A, 320, L21
Kalnajs, A. J. 1971, ApJ, 166, 275
Kent, S. M., & Dame, T. M. 1991, ApJ, 378, 131
Ma, J., Peng, Q. H., & Gu, Q. S. 1998, A&AS, 130, 449
Peng, Q. H. 1988, A&A, 206, 18
Peng, Q. H., Huang, K. L., Huang, J. H., Li, X. G., & Su, H. J. 1978, Acta Astron. Sinica, 19, 182
Peng, Q. H., Li, X. G., Su, H. J., Huang, K. L., & Huang, J. H. 1979, Sci. Sinica, XXII, 925
Shaw, M. A., & Gilmore, G. 1990, MNRAS, 242, 59
Spitzer, L. 1942, ApJ, 95, 329
Van der Kruit, P. C., & Searle, L. 1981a, A&A, 95, 105
Van der Kruit, P. C., & Searle, L. 1981b, A&A, 95, 116
Van der Kruit, P. C., & Freeman, K. C. 1986, ApJ, 303, 556
Zhao, Y. H., Peng, Q. H., & Wang, L. 2004, Chjaa, 1, 51