Chin. J. Astron. Astrophys. Vol. 3 (2003), No. 6, 499–504
(http://www.chjaa.org or http://chjaa.bao.ac.cn)

Chinese Journal of
Astronomy and
Astrophysics

# Vertical Scale Parameter Estimates for 48 Non-edge-on Spiral Galaxies *

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Received 2003 March 18; accepted 2003 June 19

**Abstract** In the first paper of this series, we directly studied the mathematical forms, symmetry of spiral structure, and the projection of galactic discs on the images, and measured the pitch angles of the spiral arms and inclination angles of the galactic discs for 60 spiral galaxies. In this second paper, we estimate the vertical scale parameters of 48 non-edge-on spiral galaxies based on the method proposed by Peng et al. and on the results given in Paper I. As we know, for edge-on disc galaxies we can obtain the vertical scale parameter from the photometry, once a mathematical form is specified for the vertical light distribution. For non-edge-on galaxies, some other methods have to be used. The statistical result was that the vertical scale parameter is comparable for edge-on and non-edge-on galaxies, although it is obtained from two very different methods.

**Key words:** galaxies: spiral galaxies – galaxies: vertical scale parameter

## 1 INTRODUCTION

Optical images of spiral galaxies, projected on the celestial sphere, are dominated by the light coming from stars. When it is face-on, the spiral structure appears to start from the central region or from the end of a bright bar. A spiral galaxy inherently consists of a halo, a bulge and a thin disc, the last shows a thickness when seen edgewise, and the thickness decreases with the radial distance from the center. A vertical scale parameter is adopted to describe the thickness of the thin disc, which certainly is an important parameter for understanding the structure of spiral galaxies.

There are two approaches (van der Kruit & Searle 1981a, b; 1982a, b; Peng 1988) to estimate this parameter. One is proposed by van der Kruit & Searle (1981a, b; 1982a, b), who investigated the surface brightness distributions in edge-on disc galaxies in optical wavebands and proposed that the locally self-gravitating isothermal sheet (Spitzer 1942) can describe the vertical light distribution

$$L(z) = L_0 \mathrm{sech}^2(z/z_0), \tag{1}$$

* Supported by the National Natural Science Foundation of China.

where $L_0$ is the surface luminosity in the plane of the galaxy, $z_0$ the vertical scale parameter and $z$ the distance from the galaxy plane. With this model, van der Kruit & Searle (1981a, b; 1982a, b) determined $z_0$ for seven edge-on spiral galaxies without an appreciable bulge. On the other hand, based on near-infrared observations of edge-on disc galaxies, Wainscoat et al. (1989) showed that there was an excess of light over the isothermal model at small distances from the galactic planes, where optical photometry is strongly affected by dust absorption. They showed that the $z$- dependence of the light in the large edge-on IC 2531 appears to be better fitted by an exponential model than by the isothermal sheet model

$$L(z) = L_0 e^{-z/z_0}. \tag{2}$$

From a detailed investigation of a statistically complete sample of highly inclined disc galaxies in the near-infrared $K'$ band, de Grijs et al. (1997) showed all their sample galaxies can have an intrinsically exponential vertical surface brightness distribution. Since the light in the $K'$ band is relatively insensitive to contamination by galactic dust, the vertical light distribution can be followed all the way down to the galactic plane (For detail see de Grijs et al. 1997). On the other hand, the vertical scale parameter for non-edge-on disc galaxies cannot be obtained from photometry. In general, an infinitesimally thin disc had to be assumed, but it is apparent that this assumption is not correct. To determine the vertical scale parameters for non-edge-on disc galaxies, Peng (1988) proposed the other approach. It is based on the formulation of the gravitational potential of both galactic discs and spiral arms with different mathematical spiral curves (Peng et al. 1978, 1979). When investigating the mass distribution within a highly flattened, axisymmetric and self-gravitating system, such as a spiral galaxy, Toomre (1963) obtained a family of exact solutions of the Poisson equation with arbitrary laws of rotation

$$\nabla^2 \phi(r, z) = -4\pi G \rho(r, z) = -4\pi G \mu(r) \delta(z), \tag{3}$$

where $r$ and $z$ denote two of the cylindrical coordinates, and $\mu(r)$ and $\delta(z)$ are the surface density and Dirac's $\delta(z)$-function, respectively. Under the quasi-stationary spiral structure theory of density wave of Lin & Shu (1964), and using the Green function method plus the Fourier-Bessel transformation of three dimensional disc galaxies, Peng et al. (1978, 1979) and Peng (1988) obtained the formulation of the gravitational potential of both galactic discs and spiral arms with different mathematical spiral curves. In other words, they generalized the Toomre models of two dimensional disc galaxies to three dimensions. They then obtained the formula that connects the vertical scale parameter and the spiral arms (details in Sect. 2). Using this formula, Peng (1988) and Ma et al. (1997a, b; 1998) obtained vertical scale parameters for 558 spiral galaxies. They (Ma et al. 1997a, 1998, 1999, 2000; Ma 2002) also acquired some statistical results between the vertical scales and other physical parameters of the galaxies. Especially, there is an important result (see Ma et al. 1997 for details) that the vertical scale parameter is comparable for edge-on and non-edge-on spiral galaxies, although it is obtained using two entirely different methods. In this paper, we obtain the vertical scale parameters for 48 disc galaxies, using Peng's formula and the results of Ma (2001, hereafter Paper I).

The outlines of this paper are as follows. In Sect. 2, we outline the principles of determining the vertical scale parameter; Sect. 3 shows how we selected our sample; and the results will be given in Sect. 4.

## 2 PRINCIPLES OF DETERMINING THE VERTICAL SCALE PARAMETER OF GALACTIC DISC WITH SPIRAL PATTERN

Spiral structure in a stellar disc is regarded as a density wave, or a wavelike oscillation that propagates through the disc in the much same way that waves propagate through violin strings or over the water surface (Binney & Tremaine 1987). The physical concept of density waves is that as matter moves very slowly within a gravitational potential well where the gravitational potential is a minimum and condensations of matter appear, i.e., the disturbance of mass density is at a maximum. In other words, the density wave of mass disturbance must be in antiphase with the gravitational potential wave of the disturbance that is caused by the mass disturbance. It is obvious that, where the gravitational potential is not at a minimum, spiral structure does not appear or if it does, only very weakly. Peng (1988) has obtained the region in which density waves cannot exist,

$$r_0 = \frac{h\sqrt{m^2+\Lambda^2}}{2}, \tag{4}$$

where $r_0$ is the polar coordinate of the starting point from which the arms of a galaxy stretch outward on the galactic plane, $m$ is the number of arms in a spiral galaxy, and $\Lambda$ is the winding parameter of the arm, $h = 2z_0$, $z_0$ the vertical scale parameter. From the fundamental assumption (details in Peng et al. 1979 and Peng 1988) the density distribution along the $z$-direction for a finite thickness disc is

$$\rho(r,\phi,z) = \frac{1}{h}\sigma(r,\phi)e^{-|z|/z_0}. \tag{5}$$

The assumption that the spiral arms can be represented by the logarithmic spiral has been confirmed by many authors (e.g., Danver 1942; Kennicutt 1981; Kennicutt & Hodge 1982; Peng 1988). Especially, in Paper I, we studied the mathematical forms, symmetry of spiral structure, and the projection of galactic discs on the images, and showed that except for small-scale distortions, the spiral arms of the sample galaxies can be represented by the logarithmic spiral form,

$$\sigma(r,\theta) = \sigma_0(r) + \frac{A}{r}e^{i(\Lambda\ln r - m\theta)}, \tag{6}$$

where $\sigma_0(r)$ is the basic axisymmetric density of the galactic disc and the next term is the disturbance density corresponding to the spiral arms. Inversely, the thickness, $h$, can be obtained by using Eq. (4) when $r_0$, $m$ and $\Lambda$ are known.

$$h = \frac{2r_0}{\sqrt{m^2+\Lambda^2}}. \tag{7}$$

When a spiral galaxy has two spiral arms that can be used to obtain the vertical scale parameter, we select the one with the smaller $r_0$.

## 3 SAMPLE

Our sample galaxies are from Paper I, in which we directly investigated the mathematical forms of 60 spiral galaxies, classified as AC 12 in the arm classification system of Elmegreen & Elmegreen (1987). These galaxies constitute a good sample that can be used to study the mathematical form of the arms. Using the results of Paper I, the vertical scale parameters of these disc galaxies can be obtained. The right ascensions and declinations (Equinox 2000.0) of these galaxies are from the Third Catalog of Bright Galaxies by de Vaucouleurs et al. (1991, hereafter RC3), and their images are taken from the Digitized Sky Survey (DSS)[1] at the Sheshan Station of Shanghai Astronomical Observatory. In this paper, we exclude 12 galaxies because of low signal-to-noise ratio or bulge saturation. In estimating the vertical scale parameter, the distance of the innermost point of the arm from the galactic center is an important parameter. If the signal-to-noise is not high enough or if there is bulge saturation, then this parameter cannot be measured.

## 4 RESULTS

From Eq. (4), we can obtain $h$ when $r_0, m$, and $\Lambda = m/\tan\mu$ are known. In Paper I, $m$ and $\mu$ have been presented. So, only the parameter $r_0$ needs to be derived. It is well known that, when the line of intersection (i.e., the major axis of the image) between the galactic plane and tangent plane is taken as the polar axis, it is easily proved that

$$r = \rho\sqrt{1 + \tan^2\gamma \sin^2\theta}, \tag{8}$$

and

$$\tan\phi = \frac{\tan\theta}{\cos\gamma}, \tag{9}$$

where $r$ and $\phi$ are the polar co-ordinates in the galactic plane, $\rho$ and $\theta$ are the corresponding co-ordinates in the tangent-plane, and $\gamma$ is the inclination of the galactic disc. The values of $\gamma$ were given in Paper I. So, if the distance between the galactic center and the starting point of the spiral arm, and the position angle of the starting point relative to the main axis of the disc are known, we can obtain the distance between the galactic center and the starting point of the spiral arm in the galactic disc (i.e. $r_0$) using Eq. (8).

The main steps of obtaining the vertical scale parameter are as follows:

1. We obtain the galaxy image from DSS according to the RA and Dec of RC3.
2. Using the DISPLAY task of IRAF software, we can enlarge the image, change its grey scale and adjust the minimum and maximum image intensity to display the image clearly.
3. We measure the distance between the galactic center and the starting point of the spiral arm, and the position angle of the starting point relative to the main axis of the disc on the image.
4. Using the Eq. (8) we can obtain the distance between the galactic center and the starting point of the spiral arm in the galactic disc (i.e. $r_0$).
5. Using Eq. (4) we then obtain the vertical scale parameter $h$ in arcmin. The vertical scale parameter $H$ in kpc is

$$H = hd, \tag{10}$$

where $d$ is the distance of the galaxy from us

$$d = \frac{v_{\rm GSR}}{H_0}, \tag{11}$$

where $H_0$ is the Hubble constant taken as $75 \mathrm{km\,s^{-1}\,Mpc^{-1}}$, and $v_{\rm GSR}$, the weighted mean radial velocity of the radio and optical redshifts of the galaxy corrected to the Galactic center, taken

[1] Based on photographic data of the National Geographic Society-Palomar Observatory Sky Survey (NGS-POSS) obtained using the Oschin Telescope Palomar Mountain, or based on photographic data obtained using The UK Schmidt Telescope.

from RC3. The results are listed in Table 1. In the table, $T$, which is taken from RC3, is the mean numerical Hubble stage index; the vertical scale parameters $h$ in arcmin are listed in column 4; the vertical scale parameters $H$ in kpc are listed in column 6.

**Table 1** Vertical Scale Parameters of 48 Disc Galaxies

| PGC | Other Names | $T$ | $h \pm dh/h$ (′) | $d$ (Mpc) | $H \pm dH/H$ (kpc) |
|---|---|---|---|---|---|
| PGC 303 | NGC7819 | 3.0 | 0.068±19.8% | 68.49 | 1.35±19.8% |
| PGC 2901 | NGC 266 | 2.0 | 0.178±23.6% | 64.31 | 3.33±23.6% |
| PGC 2949 | NGC 271 | 1.5 | 0.095±20.6% | 54.64 | 1.51±20.6% |
| PGC 5939 | NGC 622 | 3.3 | 0.047±76.7% | 69.48 | 0.95±76.7% |
| PGC 6624 | NGC 673 | 5.0 | 0.054±21.3% | 70.15 | 1.10±21.3% |
| PGC 6833 | IC 167 | 5.0 | 0.092±8.4% | 40.52 | 1.08±8.4% |
| PGC 8961 | 0218+39A | 3.0 | 0.115±20.8% | 102.37 | 3.42±20.8% |
| PGC 9236 | NGC 918 | 5.3 | 0.084±18.3% | 21.11 | 0.52±18.3% |
| PGC 9426 | NGC 945 | 4.5 | 0.189±22.9% | 59.60 | 3.28±22.9% |
| PGC 10488 | NGC 1097 | 3.0 | 0.457±7.3% | 15.91 | 2.11±7.3% |
| PGC 12412 | NGC 1300 | 4.0 | 0.244±18.3% | 19.95 | 1.42±18.3% |
| PGC 13179 | NGC 1365 | 3.0 | 0.701±23.9% | 20.55 | 4.19±23.9% |
| PGC 13584 | NGC 1417 | 3.0 | 0.091±21.4% | 54.07 | 1.43±21.4% |
| PGC 14897 | NGC 1566 | 4.0 | 0.193±4.3% | 17.60 | 0.99±4.3% |
| PGC 15018 | NGC 1530 | 3.0 | 0.362±7.2% | 34.84 | 3.67±7.2% |
| PGC 18709 | 0609+71A | 3.0 | 0.062±37.8% | 55.77 | 1.01±37.8% |
| PGC 22957 | NGC 2535 | 5.0 | 0.062±11.2% | 53.77 | 0.97±11.2% |
| PGC 23028 | NGC 2543 | 3.0 | 0.077±44.5% | 32.65 | 0.73±44.5% |
| PGC 24723 | NGC 2633 | 3.0 | 0.103±55.7% | 30.45 | 0.91±55.7% |
| PGC 24996 | IC 2421 | 5.0 | 0.053±10.7% | 57.93 | 0.89±10.7% |
| PGC 26666 | NGC 2857 | 5.0 | 0.052±10.9% | 65.56 | 0.99±10.9% |
| PGC 28630 | NGC 3031 | 2.0 | 0.905±17.6% | 3.60* | 0.95±17.6% |
| PGC 30323 | NGC 3183 | 3.5 | 0.195±7.0% | 42.85 | 2.43±7.0% |
| PGC 31926 | NGC 3347 | 3.0 | 0.275±11.1% | 37.25 | 2.98±11.1% |
| PGC 33410 | NGC 3513 | 5.0 | 0.079±52.8% | 13.39 | 0.31±52.8% |
| PGC 33860 | IC 2627 | 4.0 | 0.065±16.2% | 25.23 | 0.48±16.2% |
| PGC 34232 | NGC 3583 | 3.0 | 0.166±13.9% | 29.04 | 1.40±13.9% |
| PGC 36875 | NGC 3893 | 5.0 | 0.112±7.4% | 13.68 | 0.45±7.4% |
| PGC 36902 | NGC 3897 | 4.0 | 0.038±14.6% | 85.56 | 0.95±14.6% |
| PGC 37386 | NGC 3963 | 4.0 | 0.069±22.7% | 43.67 | 0.88±22.7% |
| PGC 38024 | 1200+41 | 4.0 | 0.057±10.3% | 82.20 | 1.35±10.3% |
| PGC 38240 | NGC 4079 | 3.5 | 0.049±12.3% | 79.65 | 1.13±12.3% |
| PGC 39479 | NGC 4246 | 5.0 | 0.048±57.2% | 48.67 | 0.68±57.2% |
| PGC 45170 | NGC 4939 | 4.0 | 0.143±12.6% | 40.11 | 1.67±12.6% |
| PGC 47404 | NGC 5194 | 4.0 | 0.172±4.0% | 7.35 | 0.37±4.0% |
| PGC 48130 | NGC 5248 | 4.0 | 0.182±13.4% | 15.04 | 0.80±13.4% |
| PGC 48371 | NGC 5260 | 4.5 | 0.041±18.1% | 85.45 | 1.02±18.1% |
| PGC 49881 | NGC 5430 | 3.0 | 0.130±10.0% | 42.09 | 1.59±10.0% |
| PGC 51169 | 1416-26 | 5.0 | 0.029±20.2% | 87.79 | 0.74±20.2% |
| PGC 54018 | NGC 5874 | 4.5 | 0.047±24.1% | 43.65 | 0.60±24.1% |
| PGC 54097 | NGC 5861 | 5.0 | 0.057±22.2% | 24.84 | 0.41±22.2% |
| PGC 54445 | NGC 5905 | 3.0 | 0.195±13.8% | 47.17 | 2.67±13.8% |
| PGC 59280 | IC1237 | 4.5 | 0.138±38.6% | | |
| PGC 64652 | 2022+05 | 4.0 | 0.037±20.8% | 66.87 | 0.72±20.8% |
| PGC 65086 | NGC 6951 | 4.0 | 0.299±5.3% | 21.93 | 1.91±5.3% |
| PGC 65269 | NGC 6956 | 3.0 | 0.114±25.1% | 64.52 | 2.14±25.1% |
| PGC 69439 | 2237+37 | 4.0 | 0.088±10.9% | 65.61 | 1.68±10.9% |
| PGC 72387 | NGC 7753 | 4.0 | 0.105±14.0% | 71.32 | 2.18±14.0% |

* The distance is taken from Faber & Gallagher (1979).

## 5 ANALYSIS OF ERRORS

Errors in the vertical scale parameter arise mainly from: (1) The position of the starting point of the arms: when the arms are not clear, this measurement contains errors. (2) The inclination of the disc: this has been estimated in Part I. Under the assumption that the arm is a logarithmic spiral, we may estimate the error. Inclination is an important parameter of a disc galaxy, since many of its observed data must be corrected for the projection. Although there are ways of measuring this parameter (see Part I for details), none of them can derive the inclination precisely. So, we add the error to the parameter when estimating the vertical scale parameter in this paper. (3) The position of the galactic center. This parameter can be derived from the RC3, but, again the derivation is not precise enough. This error is also included in our analysis. The error of the vertical scale parameter is somewhat complicated, Peng (1988) has discussed it in detail. The error estimates are derived from the formulae in Peng (1988).

**Acknowledgements** We would like to thank the anonymous referee for his/her insightful comments and suggestions that improved this paper. This work has been supported by the National Key Basic Research Science Foundation (NKBRSF TG199075402) and in part by the National Natural Science Foundation.

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