Scaling relations and fundamental plane for spiral galaxies in the J-band

Orlin I. Stanchev[1], Boris Zh. Deshev[2], Petko L. Nedialkov[1], Tsvetan B. Georgiev[2]
[1] Department of Astronomy, University of Sofia
[2] Institute of Astronomy and Rozhen NAO, Bulgarian Academy of Sciences
o_stanchev@phys.uni-sofia.bg
(Conference poster)

Abstract. The scaling relations between the fundamental parameters for 31 nearby spiral galaxies with large angular sizes, based on published elliptically averaged 2MASS brightness profiles, are built. The differences between the slopes of the relations with two different size parameters (disk scale length or disc diameter) or two kinds of magnitudes (corresponding to "disk only" or "disc + bulge" luminosity) are insignificant. The fundamental plane of the galaxies in coordinates "absolute magnitude of the disk – scale length of the disk – HI line width" is shown. The standard error of the fundamental plane fit is 0.36 mag while the standard error of the most tight scaling relation (the Tully-Fisher relation) is 0.47 mag. The derived numerical results are close to these of other authors in the I band.
Key words: galaxies: spiral, galaxies: fundamental parameters

Мащабни зависимости и фундаментална равнина за спирални галактики във фотометрична система J

Орлин И. Станчев, Борис Ж. Дешев, Петко Л. Недялков, Цветан Б. Георгиев

Посторени са мащабните зависимости между фундаменталните параметри на 31 спирални галактики от 2MASS по публикувани елиптично усреднени яркостни профили. Разликите между наклоните на зависимостите при два различни параметъра на размера (мащабна дължина на диска или диаметър на диска) или при два вида абсолютни звездни величини (съответстващи на "само диск" или "диск + балдж") са незначителни. Построена е и фундаменталната равнина за галактиките в координати "абсолютна звездна величина на диска – мащабна дължина на диска – ширина на линията HI". Стандартната грешка на модела на фундаменталната равнина е 0.36 mag, докато стандартната грешка на най-тясната от мащабноте зависимости (зависимостта на Тули-Фишер) е 0.47 mag. Получените числени резултати са близки до тези на други автори за фотометричната система I.

Introduction

The observing parameters of galaxies can be divided into two groups. The first one includes the global parameters such as luminosity (expressed usually by the absolute magnitudes of bulge, disk or bulge+disk), mass (expressed by some kinematic parameter as the central velocity dispersion σ_0 for ellipticals, the rotation velocity amplitude V for spirals or HI line width W for spirals), size (expressed by some characteristic radius like the effective radius r_e for ellipticals, disk scale length for spirals or disk diameter at a given brightness level A for spirals) and mean mass density (expressed e.g. by the mean or effective surface brightness $\langle SB \rangle_e$). The second group includes the shape parameters, like disk-to-bulge ratio D/B, mean ellipticity ϵ, velocity dispersion anisotropy $(v/\sigma)^*$, isophote shape a_4/a, etc.

Here we concentrate on the most prominent and important scaling relations between the fundamental parameters of spiral galaxies. Actually they are projections of a Fundamental Plane (FP), just like that for elliptical galaxies.

The most important projection is the Tully-Fisher (TF) relation which is a tight correlation between the amplitude of the rotational velocity V (or the HI line width W) and the absolute magnitude of the galaxy M (e.g. Tully & Fisher [1977]). It can be expressed as $M = \alpha \log V + \gamma$, where α is the slope coefficient and γ is the zero-point. This empirical relation has been used for estimating the distances to galaxies, and hence for determining the Hubble constant (e.g. Sakai et al. [2000]). The existence of the TF relation could be a result of the self-regulated star formation in disks of different mass, or a direct consequence of the cosmological evolution of mass and rotational velocity (e.g. Mao [2000]).

Some efforts have been made by many authors to search for a tighter correlation among the luminosity, rotational velocity, and disk radius for spiral galaxies. It is intriguing to know whether and how the third parameter, the galactic size, really plays some role in galaxy evolution, and how the mass and luminosity are physically related to this parameter. Koda et al. [2000b] have already done a set of numerical simulations. When the galactic size was involved as a key parameter the slope and the shape of the plane are well reproduced. The simulations show that the galactic mass and angular momentum play a prominent role during galaxy formation.

In this paper we derive scaling relations and a FP for nearby spiral galaxies with large angular sizes in the J band using fundamental parameters obtained after decomposition of the elliptically averaged brightness profiles of the galaxies published in Jarrett [2003].

1 Physical origin of the scaling relations

The scaling relations are in fact correlations between a comprehensive set of parameters: the size of the galaxy, the mean surface brightness within a given radius, the velocity of rotation, the luminosity, and the mass of the visible matter. The following two equations relate these quantities:

$$SB = \frac{L}{2\pi R^2}\ , \qquad \frac{M}{R} = cV^2.$$

Here SB is the mean surface brightness, L is the luminosity, M is the mass and R represents some scaling factor concerning the size of the galaxy. The structural parameter c contains all unknown details about the galaxy structure. Using the equations above, the galaxy size can be expressed as:

$$R = \left(\frac{c}{2\pi}\right)\left(\frac{M}{L}\right)^{-1} V^2 SB^{-1}.$$

If (M/L) and c do not vary very much, the galaxies should define a plane-like distribution in the 3D space of their global parameters (R, SB, V). For example, for elliptical galaxies the derived FP relation is (see Robertson et al. [2006]):

$$R \propto \sigma_0^{1.53} SB^{-0.79},$$

where σ_0 is the kinematic parameter for elliptical galaxies.

This result is consistent with the theoretical expectation within limitations about the variations of the dynamical structure, of the mass-to-light ratio, of the amount of the dark matter within R, of the slope of the stellar initial mass function and of other possibly varying parameters.

2 Data sample used

This work is based on the published radial brightness profiles of 31 spiral galaxies, selected from the 100 largest 2MASS galaxies (Jarret et al. [2003]). The galaxies cover the range of morphological types between Sa and Sd with inclination angles in the range 20°-70° and J-band absolute magnitudes between -22 and -25 mag. The rotational curve amplitudes lie between 200 and 700 km/s. We use the accurate distances, extinction estimations and HI line widths collected in HYPERLEDA database.

Figure 1 presents the absolute magnitude – morphological type relation for the sample of 31 galaxies in the J-band. It reproduces the known correlation between the morphological characteristics of galaxies and their luminosities. As can be seen, the most luminous galaxies in the sample belong to morphological type codes between 3 and 4. That is, early type galaxies are more luminous.

Figure 2 shows how the sample used obeys the TF relation. Here the photometry data about M_J are taken from 2MASS, while the kinematic data (W_{20} - the HI line width measured at the 20% level in km/s) are taken from HYPERLEDA database.

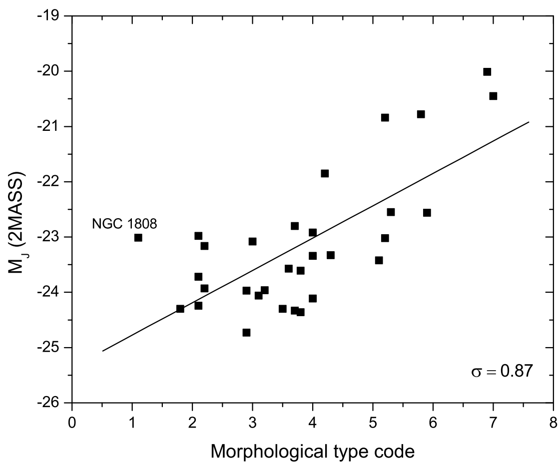

Fig. 1. Least-square fit to the luminosity – morphological type relation with J-magnitudes taken from 2MASS and type codes taken from HYPERLEDA.

3 Fundamental Plane and projected scaling relations

Now it is well known that a FP exists for the physical properties of elliptical galaxies in the 3D space defined by the central velocity dispersion, effective surface brightness and effective radius (Dressler et al. [1987]; Djorgovski & Davis [1987]; Faber et al. [1987]). Besides its remarkable distance indicator capabilities, the amazing simplicity of the FP (due to the virial theorem and the homology of structure and kinematics) allows us to investigate several physical issues: stellar population effects, rotational contribution, and dark matter content.

The generality of the concept of the FP of ellipticals makes it suitable for application to spiral galaxies as well (Persic, Salucci & Stel [1996]; Shen, Mo & Shu [2002]; Graham [2002] & Han et al. [2001]). It is therefore important to search for the FP from observational data with the galactic size as a third parameter. In principle, if M represents the photometric parameter, V - the kinematic parameter and R - the radius, then the FP relation would be expressed as:

$$M = \alpha \log V + \beta \log R + \gamma$$

Here α, β and γ are the coefficients from the fit applied to the observational data sample. For example, Kodaira [1989] gave $\alpha = -2.5$ and $\beta = -5.0$, while Koda et al. [2000a] obtained $\alpha = \beta = -3.25$. In Han et al. [2001] the FP relation for spiral galaxies in the I-band has the coefficients $\alpha = -4.75$, $\beta = -2.85$, $\gamma = -6.21$.

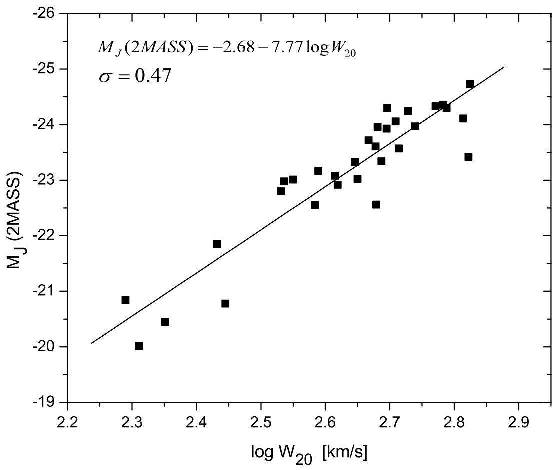

Fig. 2. Least-square fit to the Tully-Fisher relation with J-magnitudes taken from 2MASS and HI line widths $\log W_{20}$ taken from HYPERLEDA.

In this paper we consider the known scaling relations as 2D projections of the 3D FP relation, including luminosity – size (LS) relation, luminosity – velocity (LV) relation and size – velocity (SV) relation.

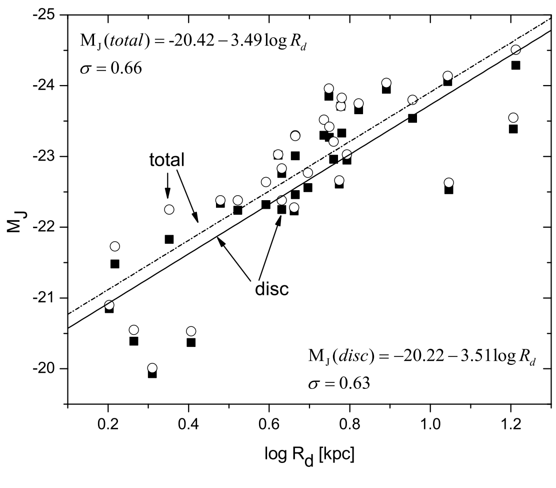

Fig. 3. Least-square fits of the luminosity – size relations with "bulge + disc" (dotted line) and "disk only" (solid line) J-magnitudes as well as disk scale lengths taken form the results of the profile decompositions (see the text).

Figure 3 presents the LS projection relation. Sometimes it is called "diameter Tully-Fisher relation". In fact, we derived two relations. The first of them, represented in Fig. 3, uses the absolute disk scale length of the galaxy and the second one (not shown here) uses the absolute disk diameter, corresponding to the 25 [mag/arcsec^2] surface brightness level. Both size parameters are derived from a disk model, obtained after decomposition of the galaxy profile into bulge and disk components in the spirit of Kormendy (Yankulov [2005]). The disk profile (as the bulge one) is fitted by Sersic's formula $I_R = I_0 \exp(-(R/R_d)^N)$, where the free parameter R_d is the disk scale length. The exponential-power number N is also a free parameter that describes the curvature of the disk profile (see Georgiev & Stanchev [2005] for details). The absolute values of the size parameters are derived through the distance modulus taken from HYPERLEDA.

The solid and dotted lines in Fig. 3 show the least-square fits for "disk only" and "bulge+disk" (labeled as total in the figures) magnitudes. Both magnitudes are derived after numerical integrations of the bulge and disk models, obtained after decomposition procedure. It can be seen that the dotted fits are shifted upwards because of the contribution of the bulge luminosity. Figure 3 shows also that the obtained standard errors of the fit for the "disc only" and "disc + bulge" case are comparable. Unfortunately, the data sample used is large and it seems hard to make more detailed conclusions. But we rather focus on the demonstration and confirmation of well known scaling relations as projections of the FP for spiral galaxies, here in the J-band.

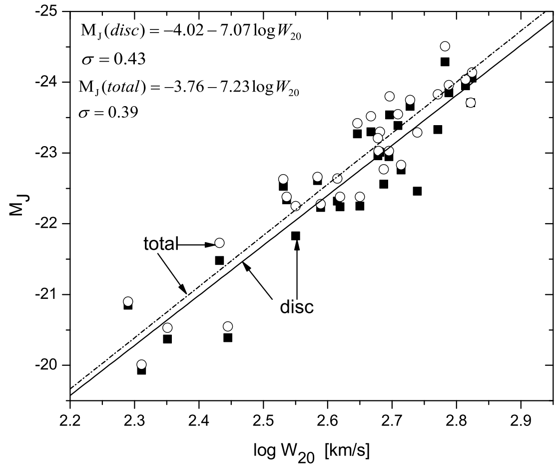

Fig. 4. Least-square fits of the Tully-Fisher relations with "bulge + disc" (dotted line) and "disk only" (solid line) J-magnitudes taken form the results of the profile decompositions (see the text).

Figure 4 shows the TF relation with the absolute J-band magnitudes obtained through the iterative decomposition procedure and the logarithm of the kinematic parameter W_{20}. This figure confirms the basic idea behind the TF relation: the bigger the galaxy is, the faster it is rotating. Just like in the previous figures, there are two lines representing two least-square fits – for the "disk+bulge" (dotted line) and the "disk only" (solid line) TF relations. The obtained zero-points and slopes are given in the figure. It can be seen that the least-square fit describes slightly better the "bulge + disc" TF relation compared with the "disk only" TF relation. Maybe the reason is uncontrolled errors in the decomposition procedure for determination of the disk scale lengths. "Bulge + disc" luminosity describes better the rotational support of the galaxy than "disc only" luminosity and that can contribute to a larger standard error of the fit for the "disc only" TF relation.

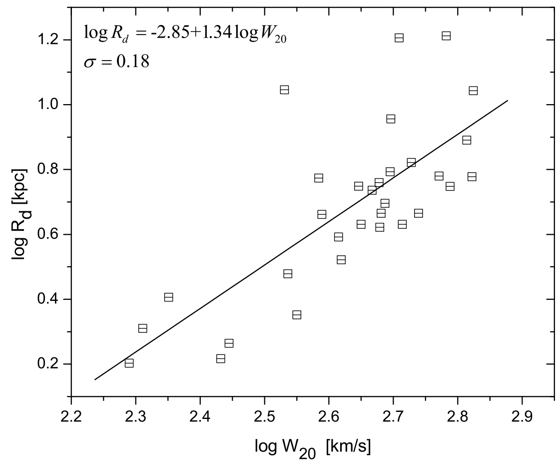

Fig. 5. Least-square fit of the size – rotational velocity relation with disk scale lengths taken from the decompositions (see the text).

Figure 5 shows the SV relation. We constructed this relation for both, the absolute disk scale lengths and absolute disk diameters, but only the relation with the disk scale length is shown. By comparing both relations we obtained that the least square fit for the disk scale length SV relation ($\log R_d - \log W_{20}$) has a larger error ($\sigma = 0.18$) than that of the absolute diameter SV relation ($\log A_d - \log W_{20}$) ($\sigma = 0.14$). Probably this description is due to the three outlying points in the ($\log R_d - \log W_{20}$) relation. Figure 5 expresses the known correlation between the size and the rotational velocity of the galaxies: larger galaxies are faster rotators.

Figure 6 shows the FP in the space of the global parameters luminosity, size and rotational velocity for our sample of 31 2MASS spiral galaxies with large angular sizes. As it can be seen in the figure, the distribution of the points in the 3D space is well projected into each plane, showing quite good correlation between each pair of parameters. These are the known scaling relations for spiral galaxies - the LV (TF) relation, the LS relation, and the SV relation. Here the luminosity parameter is the "disk only" J-absolute magnitude. The size parameter is the absolute disk scale length (in kpc) and the kinematic parameter is the HI line width measured at the 20% level (in km/s). The empty squares show the 3D distribution of the points and the filled squares show the projections of the FP, corresponding to the scaling relations for the spiral galaxies. Figure 7 represents the FP in the 3D space as a result of a least-square plane fit. Based on the sample of 31 2MASS spiral galaxies, we obtain the following Fundamental Plane relation:

$$M_J(disc) = -5.29 \log W_{20} - 1.33 \log R_d - 7.79.$$

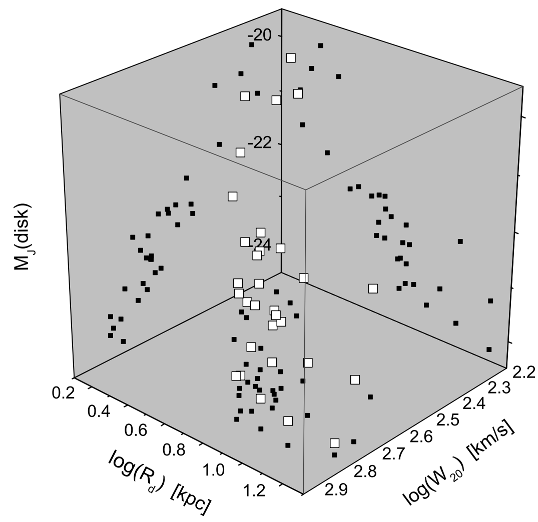

Fig. 6. Fundamental Plane represented though its 2D projections, that are the galaxy scaling relations.

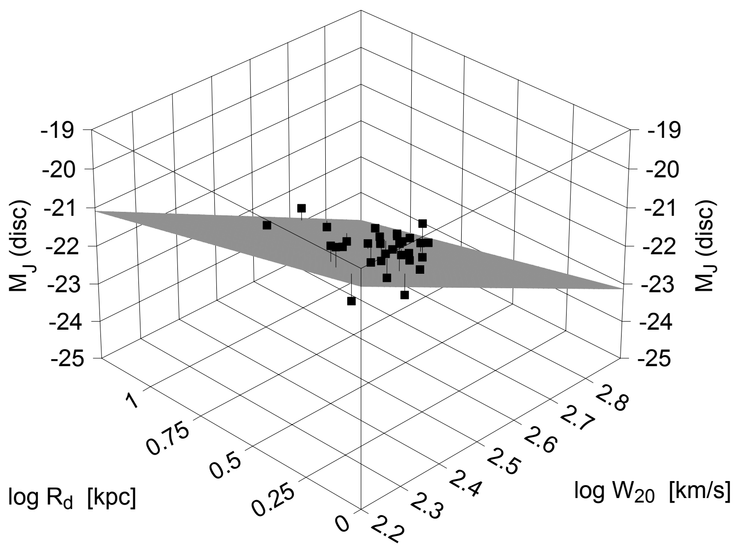

Fig. 7. The obtained Fundamental Plane relation.

Table 1. Fundamental Plane relations for 6 different sets of global parameters

FP relation	α	β	γ	σ
$(\log W_{20} - \log A_d - M_{total})$	-5.679	-1.307	-5.833	0.362
$(\log W_{20} - \log R_d - M_{total})$	-5.723	-1.125	-6.698	0.351
$(\log W_{20} - \log A_d - M_d)$	-5.679	-1.166	-5.870	0.404
$(\log W_{20} - \log R_d - M_d)$	-5.289	-1.323	-7.796	0.361
$(\log W_{20} - \log A_d - M_{2MASS})$	-5.160	-2.195	-6.158	0.369
$(\log W_{20} - \log R_d - M_{2MASS})$	-6.703	-0.795	-4.945	0.458

The standard error of the least square fit is 0.36 mag. The coefficients of this FP are close to the coefficients for the I-band data derived by Han et al. [2001], given in Section 3.

Results

The results of this work can be summarized as follows:

- We derived scaling relations between the global parameters of the spiral galaxies in the J-band. We found close values of the relation slopes in the cases of two different size parameters (the disk scale lengths R_d or disc diameters A_d) and two kinds of magnitudes (corresponding to "disk only" or "disc + bulge" luminosity). The coefficients of our relations in the J-band are comparable with the same coefficients of Han et al. [2001] in the I-band .

- We derived the FP coefficients $\alpha = -5.29$, $\beta = -1.33$, $\gamma = -7.79$. The standard error of the fundamental plane fit is 0.36 mag while the standard error of the most tight scaling relation (the Tully-Fisher relation) is 0.47 mag. Our results are close to these of Koda et al. [2000a] and Han et al. [2001] in the I band.

References

Djorgovski S. & Davis M., 1987, *ApJ 313, 59*

Dressler A., Lynden-Bell D., Burstein D., Davies R. L., Faber S. M., Terlevich R.J. & Wegner G., 1987, *ApJ, 313, 42*

Faber S. M., Dressler A., Davies R. L., Burstein D., Lynden-Bell D., Terlevich R.J., & Wegner G., 1987, *in Nearly Normal Galaxies, From the Planck Time to the Present, ed. S. M. Faber (NY: Springer), 175*

Georgiev Ts. B. & Stanchev O. I., 2005, *Bulg. J. Phys., 32, 65*

Graham A. W., 2002, *MNRAS, 334, 721*

Han J., Deng Z., Zou Z., Wu Xue-Bing & Jing. Y., 2001, *PASJ, 53, 853*

Jarret T.H., Chester T & Outri R., 2003, *ApJ 125, 525*

Koda J., Sofue Y. & Wada K., 2000a, *ApJ, 531, L17*

Koda J., Sofue Y. & Wada K., 2000b, *ApJ, 532, 214*

Kodaira K., 1989, *ApJ, 342, 122*

Mo H. J. & Mao S. 2000, *MNRAS, 318, 163*

Persic M., Salucci, P. & Stel F., 1996, *MNRAS, 287, 27*

Robertson B., Cox Thomas J., Hernquist L. et al., 2006, *ApJ, 641, 213*

Shen S., Mo H. J. & Shu C., 2002, *MNRAS, 331, 259*

Tully R. B. & Fisher J. R., 1977, *A&A, 54, 661*

Sakai S., Mould J. R., Hughes S. M. G., Huchra J. R., Macri L. M., Kennicutt R. C. et al. 2000, *ApJ., 529, 698*

Yankulov I., 2005, *Master Thesis, Department of Astronomy, University of Sofia*