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On Photometric Plane of Bright Galaxies in Coma.

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ABSTRACT

We have obtained the quantitative morphology of a sample of 116 bright galaxies in Coma cluster. The galaxies were classified according with their B/T ratio, obtained from the decomposition of their isophotal surface brightness profiles into bulge and disc components. Theywere grouped in four classes: Ellipticals, S0, early and late-type spirals.

We analyze and discuss the location of the bulges of the spirals, S0s and ellipticals in the Photometric Plane (PhP). A discussion on the physical meaning of the PhP take us to define and propose a new coordenates sistem in which the three axes are photometric ones and are related by the Virial Theorem, the Virial Photometric Plane (V-PhP). The V-PhP is defined with the structural parameters $F(n)$, μ_o and r_e, being $F(n)$ an increasing monotonic function of n. We have obtained both the Photometric and Photometric Virial Planes for each galaxy group in the sample.

In both representations, and within 3 σ uncertainty, Spiral bulges grouped together and ellipticals sit on a different plane. This tells us that the formation mechanism of bulges of Spe and Spl galaxies is the same.

The Photometric Plane obtained for the S0 galaxies is different that the one for Spiral bulges, and it is very close to the Elliptical's Plane. However this behaviour changes when using the Virial Photometric Plane, where S0s joint the bulges Plane detaching from the Ellipticals. This add more controversia to the origin of S0 and, with the asuption that this class is well represented by Sersic Profiles, its location in the Virial Photometric Plane would indicate that the bulges of S0s are formed by mechanisms similar those of the bulges of Spe and Spl.

Subject headings: clusters: globular, peanut—bosons: bozos

1. Introduction

Bulges of S0 galaxies and Ellipticals are distributed in a thin plane called the fundamental plane (FP) (Djorgovski & Davis 1987; Dressler et al 1987; Falcón-Barroso et al 2002 and references therein). The FP relates the structure (effective surface brightness and radii) and the kinematic (central velocity dispersion) of bulges and elliptical galaxies, and contains useful clues about the physics of these systems. It is related with the Virial theorem, and provides information about the differences in stellar population, internal structure, origin or kinematics of bulges of spirals and elliptical galaxies (Prugniel & Simien 1994, 1996, 1997).

The FP and the Tully-Fisher (TF) relation are empirically calibrated scaling relations that can also be used as distant indicators. While the photometric parameters of the FP and TF relation can be economically acquired, the spectroscopy requires more observational investment. For this reason, alternative representations of the FP were obtained by substituting the central velocity dispersion (σ) with photometric parameters, for example: broad-band colors (de Carvalho & Djorgovski 1989) or relative luminosities (Scodeggio et al 1997). Recently, Graham et al (2001) have shown that the index n of the Sersic surface brightness profiles of elliptical galaxies can be used as effectively as the central velocity dispersion for predicting the mass of their central black holes. This tight correlation between n and σ provides another representation of the FP, called the photometric plane (PhP).

Graham (2002) showed that there is a common PhP for the bulges of S0s and elliptical galaxies. He also demonstrated that the FP has $\approx 15-30$ per cent less scatter that the photometric plane. Other authords like Khoroshahi et al (2000) constructed a common near-infrared photometric plane using the Sersic index n, the effective radius, r_e, and the central surface brightness, μ_o, for a sample of ellipticals and early-type bulges of galaxies.

Möllenhoff & Heidt (2001) found a similar relation for a sample of bulges of spiral

galaxies from Sa to Sc types. They pointed out that no correlation was obtained when μ_o is substituted by the effective surface brightness (μ_e) or the mean surface brightness inside r_e. So, the physical meaning of such correlation between the photometrical parameters of the Sersic surface brightness profiles is not clear yet. Koroshahi et al (2000) demonstrated that such correlation is not just an internal correlation between the chosen structural parameters of the profiles.

In this work we study the photometric plane for a sample of 116 bright galaxies in Coma cluster. After obtaining the photometric parameters of the galaxies of the sample, a classification into four main groups is made, namely ellipticals, S0, early and late spirals. We compare the photometric planes of the different categories from ellipticals to bulges of late-type galaxies, and the physical meaning of this correlation is studied and discussed.

2. The Sample

The observations were taken with the Wide Field Camera (WFC) at the prime focus of the INT 2.5m telescope at the Roque de los Muchachos Observatory (La Palma) on April 2000. Four pointing of the Coma cluster were obtained under photometrical conditions, covering a total area of $\approx 1 deg^2$. The images were obtained using the r'Sloan-Gunn broad band filter of the WFC. For a detail description of the observations, data reduction and calibration we refer to the reader to Iglesias-Paramo et al (2002, 2003).

The structural parameters of the galaxies were obtained fitting a Sersic profile for the bulges plus an exponential disc, using the algorithm developed by Trujillo et al (2001). This algorithm takes into account both the elliptical shape of the galaxies and the effects of the seeing in the surface brightness profiles. Previously, we run the algorithm on simulated galaxies with scales and magnitudes similar to those in Coma cluster, in order to determine the limiting magnitude for which we recover reliable structural parameters (see Trujillo et al 2001; Aguerri & Trujillo 2002). The simulated galaxies were build up with a minimum area of 200 pixels in order to get reliable decompositions. The real galaxies were also selected according with this criterion. This limiting magnitude for which the recovered structural parameters were obtained within an error less than 20% was $m_r = 17$ (for a detailed description of the simulations see Aguerri et al 2003, in preparation). We obtained from the images 280 galaxies with $m_r \leq 17$, assuming that Coma members are those with $4000 \leq cz \leq 10000$ km s^{-1} and using the catalog of Godwin et al (1983), we ended with a total of 215 galaxies with $m_r \leq 17$ and belonging to Coma cluster. Our membership criteria was the same as used by Edwards et al (2002).

2.1. Galaxy classification

A first classification consisted on grouping the galaxies just by their luminosity. We distinguish two main systems: bright and dwarf objects. Dwarf galaxies are those with $M_B \geq -18$ and bright ones those with $M_B < -18$. This classification gave 99 dwarfs and 116 bright objects. Hereafter we will study only the 116 bright galaxies. The B magnitudes of the objects were taken from Godwin et al (1983).

The isophotal surface brightness of the bright galaxies were decomposed in bulge and disc components. The surface brightness profile of the bulge was modeled by a Sersic (1968) law, given by:

$$I_b(r) = I_e 10^{-b_n\{(r/r_e)^{1/n}-1\}} \quad (1)$$

where n is the Sersic index of the profile, r_e is the effective radius, which is the radius enclosing half of the total luminosity of the profile, and I_e is the effective intensity. The constant, b_n, is given by: $b_n = 0.868n - 0.412$ (see Caon et al xxx). The disc surface brightness was modeled by an exponential disc (Freeman 1970), given by:

$$I_d(r) = I_o e^{-r/h} \quad (2)$$

where I_o is the central surface brightness and h is the scale length of the profile. The free parameters I_o, h, I_e, r_e and n were fitted minimizing the χ^2 on the isophotal surface brightness profiles of the galaxies using a Levenbeg-Marquan routine (see Trujillo et al 2001, Aguerri et al 2003, in preparation). According with the B/T ratio (Simien & de Vaucouleurs 1986) the galaxies were classified in different morphological types. Following our simulations we recovered reliable B/T ratios for the simulated galaxies with $B/T \leq 0.8$. Objects with $B/T > 0.8$ were classified as Elliptical galaxies (E) and their surface brightness profiles were fitted only by a Sersic law. Objects with $B/T \leq 0.8$ were classified is four types: late-type galaxies (Spl) $0 \leq B/T \leq 0.24$; early-type (Spe) $0.24 \leq B/T \leq 0.5$; lenticulars (S0) $0.5 \leq B/T \leq 0.6$ and ellipticals with disc (dE) $0.6 \leq B/T \leq 0.8$. The total number of objects of each type were: 16 Spl, 20 Spe, 13 S0, 12 dE and 34 E. The remaining to 116 objects were edge on galaxies, irregular objects or galaxies with prominent bars for which the surface brightness decomposition was not made. The adopted values of B/T for the classification were taken from Simien & de Vauvouleurs (1986). We have compared our classification with visual classifications when it is available. In general the B/T ratio decreases from early to late type galaxies. But, with a big scatter specially for the earliest types of objects, making hard the distinction between S0, E and dE. Hereafter we will considered the E and dE

only one class of objects, called Ellipticals (E). We will keep the S0 galaxies as a separate group. These objects are the transition between disc dominated galaxies (spirals) and bulge dominated systems (ellipticals).

3. The Photometric Plane of the galaxies in Coma

We have obtained and represented (see Fig. 1) the photometric plane formed by the structural parameters n, r_e and μ_o; being μ_o the central surface brightness of the Sersic profiles of the bulges and elliptical galaxies in Coma cluster. The expression of such plane is given by: $log(n) = Alog(r_e) + B\mu_o + C$; the parameters ($A, B$ and C) were obtained minimizing the scatter in $log(n)$, and the errors were computed by bootstrap. Table 1 gives the values of the constants of the photometric plane for different the types of galaxies. Khoroshahi et al (2000) determined the photometric plane for a sample of elliptical galaxies in Coma from observations in the near-IR K-band. The angle between that plane and our is 3.66 ± 1.53. This angle is slightly more than the 2 σ uncertainty, which implyes a good agreement between both photometric planes. It should be noted that the biggest source of disagreement could be due to the fact that the photometric planes are computed in different bands and the structural parameters are also obtained in a different way. They also obtained a photometric plane for a sample of early-type objects. This sample is the sample of Peletier & Balcells (1997), which is formed by galaxies from S0 to Sb types. This is the same set of galaxies than those contained in our S0 and Spe groups. The difference between our photometric plane from S0+Spe objects and the plane from the early-type galaxies of Khorsroshahi et al (2000) is again small: 3.61 ± 1.91.

Khorsroshahi et al (2000) conclude that due to the small angle between the photometric planes of their E and early-type bulges, both type of systems are in a common photometric plane. In Table 2 we show the angles between our photometric planes for the different type of objects. We can see that the photometric planes corresponding to Spe and Spl galaxies are very similar, and different than the planes of S0 and E+dE, which in turn are very close to each other. Then, we can conclude that the photometric planes continuously change from bulges of Spl and Spe to elliptical galaxies. The bulges of S0 galaxies has a photometric plane close to the E+dE. Notice that the most important difference of our work with Khorsroshahi et al (2000) is that we have considered the bulges of S0 galaxies in a separate class than the bulges of early-type ones. As we have proved before if we would include the bulges of S0 galaxies with Spe the results would have been similar to those reported by Khorsroshahi et al (2000).

4. The Virial Photometric Plane

One interesting question still not solved is the physical meaning of the photometrical plane: is the photometrical plane related with the Virial theorem as the fundamental plane is?. There is an empirical correlation between the central velocity dispersion, σ, and the index n of the Sersic profiles (Graham 2002). Figure 2 shows this correlation for elliptical galaxies in Coma, Virgo and Fornax. The correlation is $log(n) \propto 0.76 log(\sigma)$, and the Pearson coefficient is $r = 0.85$. Although this correlation is quite strong, it can be seen from Fig. 2 that it has an important scatter. This scatter could be due to differences in the M/L ratios among the elliptical galaxies. Assuming Virial equilibrium we have computed the M/L for our elliptical galaxies in Coma with measured σ, with the result that the M/L ratio is constant for all objects except for a few of them ($\approx 15\%$). This small number of objects can not account for the big scatter in the log(σ)-log(n) relation. So we conclude then that scatter is intrinsic and it is due to errors in the determination of the n Sersic index parameter.

Given that the fundamental plane is a relation between σ, r_e and μ_e, it can be thought that the photometric plane can be related with the Virial theorem due to the relation between n and σ. The Virial theorem can be expressed as:

$$K_k \sigma^2 = K_s (M/L) L r_e^{-1}, \tag{3}$$

where K_k and K_s are kinematical and gravitational scaling parameters, M/L is the mass-to-light ration of the object, L is the total luminosity and r_e is the effective radius. For a Sersic surface brightness profile the total luminosity is given by: $L = f(n) I_o r_e^2$, where $f(n) = (2\pi n \Gamma(2n))/(b_n ln(10))^{2n}$ is a function only dependent on n, and I_o is the central intensity of the Sersic profile. Then, assuming the empirical relation between σ and n, the Virial theorem can be expressed as:

$$log(F(n)) = cte - 0.4\mu_o + log(r_e), \tag{4}$$

where $F(n) = (b_n ln(10))^{2n} n^{1.63}/(2\pi\Gamma(2n))$. The constant is related with the M/L ratio and the scaling parameters of the objects. The Virial theorem tells us that for a Sersic profile the quantities $F(n)$, μ_o and r_e are in a plane. So, the Photometric Plane formed by the parameter n is not directly related with the Virial theorem as the FP does. The functions $log(n)$ and $log(F(n))$ have only in common that they are monotonic and always growing functions of n. We have fitted the parameters of the plane: $log(F(n)) = \alpha log(r_e) + \beta\mu_o + \gamma$ (hereafter named the Virial Photometric Plane) for the different types of galaxies in our

sample (Table 3). Notice that the coeficients of the elliptical's plane are the closest ones to the Virial coeficients given in eq. (4), and the most different coeficients are those corresponding to the bulges of spirals galaxies. This result would imply that ellipticals are systems closer to the virialization hipothesis reflected in the Virial Theorem.

5. Discussion and Conclusions

Table 4 gives the angles between the Virial Photometric Plane of the different types of galaxies in our sample. First result is that the angles are smaller than those obtained for the Photometric Plane (see Table 2). In both representations, and within 3 σ uncertainty, Spiral bulges groupe together and ellipticals sit on a different plane. This tells us that the formation mechanism of bulges of Spe and Spl galaxies is the same. Courteau et al (1996) found for a sample of galaxies from Sa to Sm that the ratio of the scale lengths of the bulge and disc is the same for all type of galaxies. Such correlation is best understood in a model where the formation mechanism is the same for all galaxies, being the disk which is form first and the bulge naturally emerges in closely coupled to the disk. Graham & Prieto (1999) reanalyzed the data from Courteau et al (1996) and found that the scale length ratio slightly change with the Hubble type.

The Photometric Plane obtained for the S0 galaxies is clearly different that the one for Spiral bulges, and it is very close to the Elliptical's Plane. However this behaviour is turned upside down when using the Virial Photometric Plane, where SOs joint the bulges Plane detaching from the Ellipticals. This add more controversia to the origin of SO and, with the asuption that this class is well represented by Sersic Profiles, its location in the Virial Photometric Plane would indicate that the bulges of S0s are formed by mechanisms similar those of the bulges of Spe and Spl. However several mechanisms have been proposed for the formation of S0 galaxies and still is not clear if they are really a different kind of galaxies or they are just modified spiral by some dynamical processes (Prieto et al 2003).

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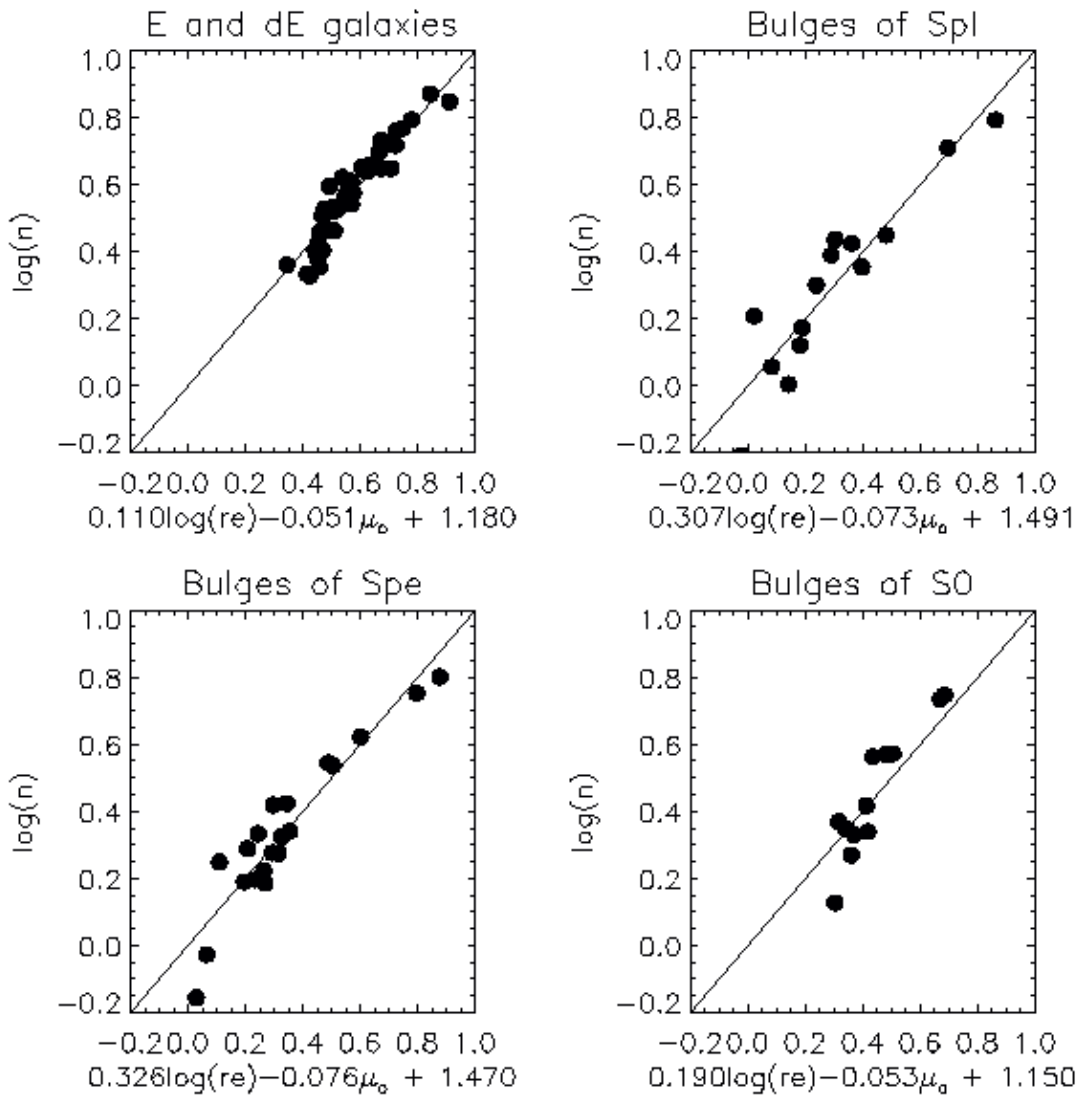


Fig. 1. Photometric planes of the different galaxy types..

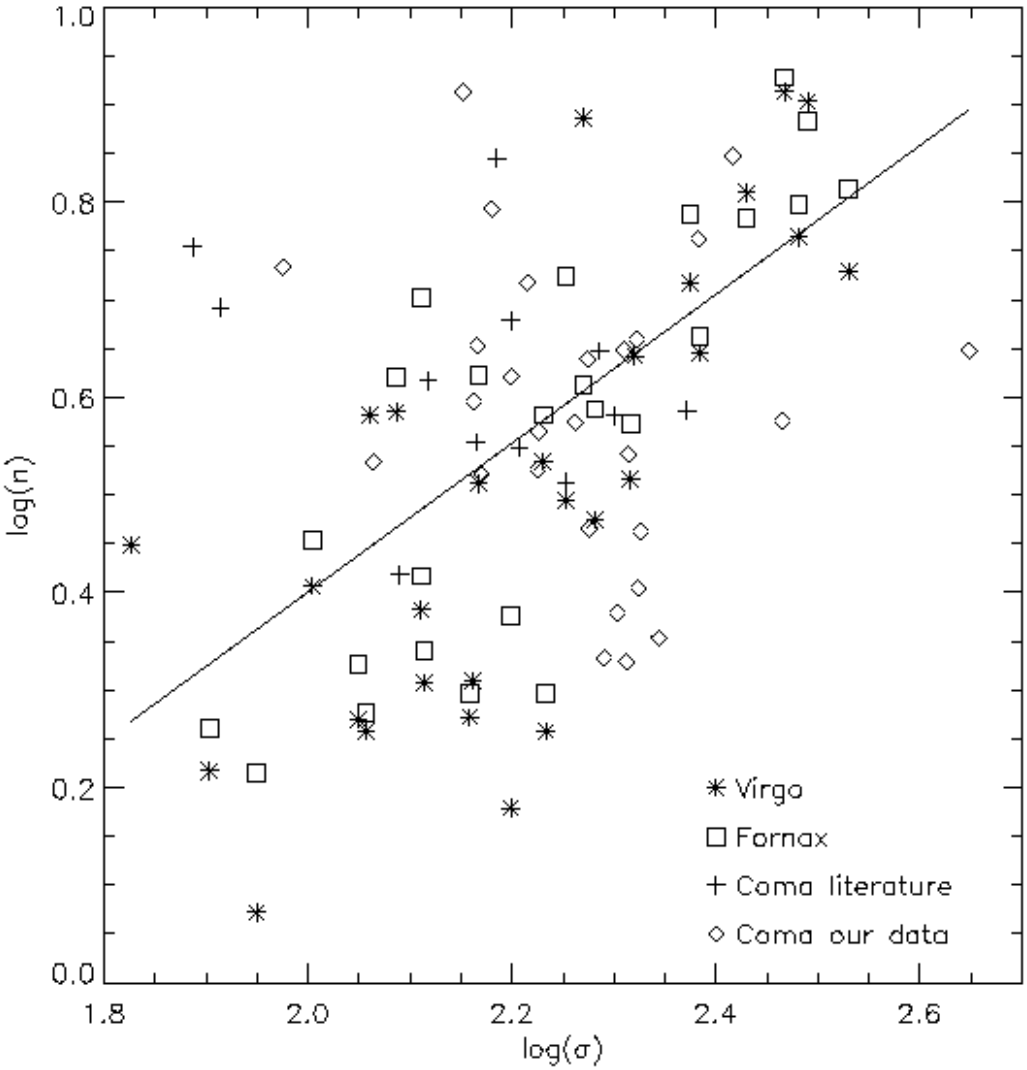


Fig. 2. *log*(σ)-*log*(n) relation for Elliptical galaxies in Virgo, Fornax and Coma clusters. The data for Fornax was taken from Graham (2002), Virgo and Coma literature were obtained drom Trujillo. The dispersion velocities of our Coma galaxies were obtained from Scodeggeio et al (1998).

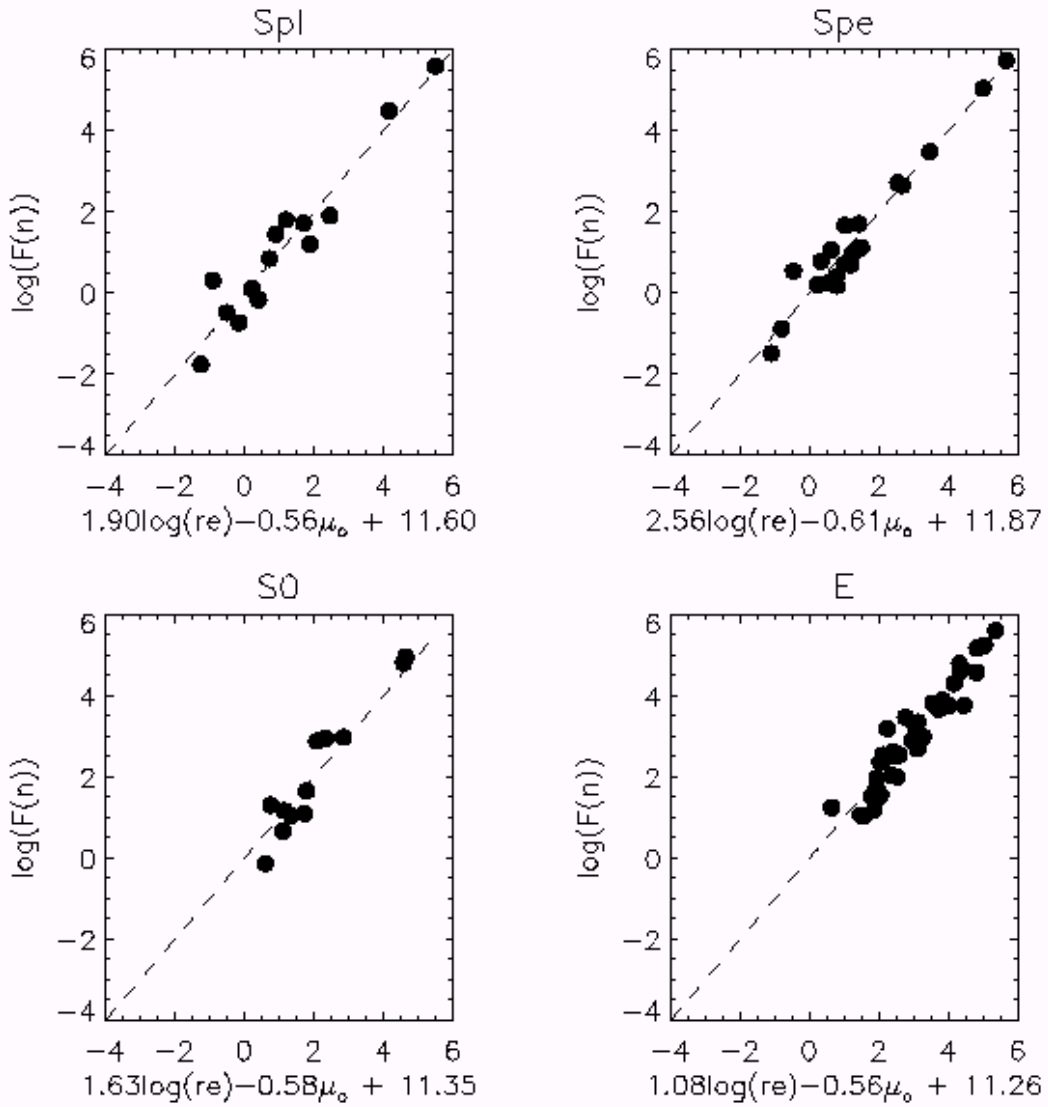


Fig. 3. The projections for the Virial photometrical plane.

Table 1. Parameters of the Photometric plane

Galaxy type	A	B	C	RMS
E	0.110±0.031	-0.051±0.010	1.180±0.105	0.005
S0	0.190±0.022	-0.053±0.009	1.150±0.086	0.025
Spe	0.326 ±0.039	-0.076±0.013	1.470±0.139	0.013
Spl	0.307 ±0.028	-0.073±0.012	1.491±0.123	0.027
E+S0	0.120±0.012	-0.050±0.010	1.153±0.077	0.003
Spe+Spl	0.245±0.021	-0.073±0.012	1.447±0.112	0.013

Table 2. Angles between the photometric planes of the different type of galaxies

	E	S0	Spe	Spl
E		4.476±1.311	11.820±1.661	10.824±1.415
S0			7.374±1.452	6.377±1.177
Spe				0.997±0.976

Table 3. Parameters of the Virial photometric planes

Galaxy type	α	β	γ	RMS
E	1.08±0.08	-0.56±0.08	9.91±0.98	0.033
S0	1.63±0.13	-0.58±0.07	9.95±0.99	0.015
Spe	2.56±0.21	-0.61±0.06	10.42±0.95	0.094
Spl	1.90±0.12	-0.56±0.06	10.26±0.90	0.150
E+S0	1.12±0.09	-0.56±0.07	9.87±0.98	0.015
Spe+Spl	1.66±0.12	-0.57±0.06	10.00±0.91	0.075

Table 4. Angles between the Virial photometric planes of the different type of galaxies

	E	S0	Spe	Spl
E		2.69±0.80	6.68±0.96	3.82±0.72
S0			3.99±1.05	1.14±0.65
Spe				2.86±1.07