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The relation between the virial theorem and the fundamental plane of elliptical galaxies

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Abstract. The analysis of the properties of a sample of elliptical galaxies for which the kinetic energy of both random and rotational motions are consistently defined, shows that more than half of the so-called 'tilt' of the fundamental plane of elliptical galaxies is accounted for by the non-homology in the dynamical structure of the systems. We find that the kinetic energy of random motions is proportional to $\sigma_0^{1.6}$ instead of σ_0^2. We also confirm that some fraction of the tilt is accounted for by the rotation. The remaining 30% of the tilt, on the other hand, can be easily explained by stellar population effects and, possibly, by spatial non-homology. We find that, in the present sample, there is no correlation between mass-to-light ratio and luminosity. We are thus led to conclude that the existence of the fundamental plane can be consistently explained by the virial theorem, or, in other words, that elliptical galaxies are non-homologous virialized systems. The presence of the dynamical non-homology casts some doubts on the use of the FP as a distance indicator.

Key words: galaxies: elliptical and lenticular, cD – galaxies: kinematics and dynamics – galaxies: structure – galaxies: fundamental parameters – galaxies: statistics

1. Introduction

The two-dimensional nature of the relations existing between the global properties of elliptical galaxies also known as the 'fundamental plane' (hereafter FP; Dressler *et al.* 1987, Djorgovski & Davis 1987), leads to three, yet largely unanswered, questions: i) why is the FP so thin (i.e. why is that relation so tight); ii) why is the FP 'tilted' (i.e. why elliptical galaxies don't seem to obey the virial theorem); and, iii) why does the FP itself exist (i.e. what causes the properties of elliptical galaxies to be so 'systematic'). Due to the primary relevance of these questions for the problems connected to the origin, the nature, and the evolution of galaxies, much work has been devoted to the analysis of the properties of the FP and to their possible interpretations (e.g. Djorgovski & Santiago 1993 (=DS93), Djorgovski 1993, Djorgovski *et al.* 1995, and references therein) . In particular, the problem of the tilt of the FP, which will be addressed in the present paper, can be summarized as follows. The (scalar) virial theorem (hereafter 'VT') connects the potential energy V and the kinetic energy T of a stationary self-gravitating system by the relation $2T + V = 0$ (e.g. Landau & Lifshits 1976).

By writing the VT in terms of a set of the above mentioned quantities (e.g the effective radius r_e, the central velocity dispersion σ_0, and the mean surface brightness within the effective radius I_e; hereafter we shall refer to them as the 'observables'), one obtains:

$$r_e = C\sigma_0^2 I_e^{-1}\left(\frac{M}{L}\right)^{-1}, \quad (1)$$

where (M/L) is the mass-to-light ratio, and C is a combination of terms linking the observables to the corresponding physical quantities (namely, the central velocity dispersion to the kinetic energy, the effective radius to the 'gravitational' radius, and the effective surface brightness to the overall light profile, see e.g. DS93).

On the other hand, the FP writes:

$$r_e = c\sigma^a I_e^b , \quad (2)$$

where a and b are constants which depend on the sample, on the photometric band (e.g. DS93, Djorgovski *et al.* 1995, Pahre *et al.* 1995, and references therein), and also on the fitting procedure adopted (we shall review this last point in a forthcoming paper). The various estimates of these constants span over a rather wide range. For instance, a=1.4, $b = -0.85$ (Bender *et al.* 1992, hereafter BBF92); $a = 1.04$, $b = -0.88$ (Saglia *et al.* 1993); $a = 1.56$, $b = -0.94$ (Djorgovski *et al.* 1995). The 'thickness' of the FP is typically $\sim 12\%$ in all the three variables. For what the tilt of the FP is concerned, the problem is that the values of a and b differ from those predicted by the VT ($a = 2$, $b = -1$). When written in logarithmic form, the two planes appear to be tilted by an angle of $\sim 15°$.

If ellipticals (hereafter 'E's') were homologous systems, C would be constant, and the consistency of Eqs. (1) and (2) would imply that $M/L \sim L^\beta I_e^\gamma$. The tilt of the FP would then imply a systematic change of the mass-to-light ratio along the FP.

Many attempts have been devoted to explain the tilt of the FP in terms of, e.g., varying amount and/or varying concentration of dark-to-luminous matter in galaxies with different mass (Ciotti *et al.* 1995); differences in the initial mass function of stars (Djorgovski 1988, Renzini & Ciotti 1993); metallicity effects, which are expected to be stronger in the B bandpass due to line blanketing (the FP tilt decreases indeed in the near infrared; e.g. DS93, Pahre *et al.* 1995 and references therein).

All these explanations, however, fight against the tightness of the FP, which requires a high degree of regularity in the trend of the M/L ratio and which, in turn, implies a fine tuning of the global properties of ellipticals during their formation and evolution. A fine tuning which is difficult to reconcile with any formation and secondary evolution scenarios. A complementary way is to drop off the assumption of homology. The non-constancy of C would then reflect the non-linearity of the scaling relations. The photometry (e.g. Michard 1985, Schombert 1987, Kormendy & Djorgovski 1989, Caon *et al.* 1993 (=CCD93), Djorgovski 1993, Michard & Marchal 1994), the kinematics (e.g. Davies *et al.* 1983, Illingworth 1983, Capaccioli & Longo 1994) as well as theoretical arguments (e.g. Hjorth & Madsen 1995, Kritsuk 1996 and references therein) show that E's do not constitute a family of homologous structures. There are also some recent theoretical evidences showing that non-homologous families of E's may result from (dissipationless) hierarchical merging (Capelato *et al.* 1995). We thus expect C to depend in some way on the phase-space structure and on the history of the individual galaxies.

Prugniel & Simien (1996, hereafter PS96), from a detailed analysis of the correlation of the residuals of the FP to the UBVRI colors and to the Mg_2 index, found that half of the observed tilt is accounted for by the effects of stellar populations, and argue in favour of a constancy of M/L. Pahre *et al.* (1995), from a study of the FP in the K band, suggest that the tilt might be explained by non homology in both the spatial structure and in the dynamics of galaxies.

The problem of the role played by rotation on the characteristics of the FP has been often addressed. While the VT involves the total kinetic energy, the FP is usually derived in terms of σ_0 only, which may not contain enough information on the dynamical status of a system. By including the rotational term in the FP, DS93 obtained only marginal changes in their solutions. BBF92 found no correlation of the residuals of the FP with the so-called anisotropy parameter $(V_m/\sigma_0)*$, while Bender *et al.* 1994 found that the thickness of the FP decreases by $\sim 20\%$ if the rotation is taken into account. D'Onofrio *et al.* (1996) found that the residuals of both the FP and the $D_n - \sigma$ relation marginally correlate with V_m and with (V_m/σ_0).

The first thorough analysis of the role of the rotation in the FP was that of Prugniel & Simien (1994, hereafter PS94, and PS96) who find that the residuals of the FP correlate with the rotational support term with the expected slope. Furthermore, they derived the exact 'rotational' contribution to the tilt (see also below).

In this paper we will address the problem of the tilt of the FP from the dynamical point of view.

In Sect. 2 we present the set of the data, briefly outline the way in which the kinetic energies of random and rotational motion were computed, and re-derive the FP in terms of the kinetic energies. A discussion of the role of non-homology in the dynamical structure is presented in Sect. 3, while the conclusions are drawn in Sect.4.

2. The FP and the kinetic energy

The sample for the present investigation consists in 40 'bona fide' (giant and intermediate) elliptical galaxies for which 'extended' kinematical data (rotation curve and velocity dispersion profile) are available. The sample comes from a previous work (Busarello *et al.* 1992, hereafter BLF92) aimed to study the relative contributions to the kinetic energy of random and rotational motions.

The data, listed in Table 1, are: the effective semi-major axis r_e; the (one dimensional) velocity dispersion derived from the relative kinetic energy (computed inside r_e) σ; the rotation velocity, also derived from the relative kinetic energy (computed inside r_e) V; the central velocity dispersion σ_0; the surface brightness within the effective radius I_e.

The two last data sets are taken from BBF92, while r_e, σ and V come from BLF92 and Busarello *et al.* 1996. The way in which the kinetic energies $\frac{1}{2}V^2$ and $\frac{3}{2}\sigma^2$ were derived is the following (further details, as well as the sources of the data, may be found in BLF92). In computing the kinetic energy T we started from the assumption that the galaxies were isotropic oblate spheroids with spatial density given by the deprojection of the $r^{\frac{1}{4}}$ law. These assumptions are rather realistic since E's possess in most cases only moderate degrees of triaxiality and anisotropy (e.g. Busarello *et al.* 1989, BLF92, DS93, Capaccioli & Longo 1994 and references therein). Galaxies are assumed to be viewed edge-on. This assumption is unavoidable, and leads to underestimating the rotational contribution (although the anisotropy parameter $(V/\sigma)*$ has been shown in BLF92 not to be strongly affected). The assumption of cylindrical symmetry for the rotation field, on the other hand, may lead to overestimating V with respect to a spheroidal-symmetric field. The assumption of a $r^{\frac{1}{4}}$ law instead of the more general $r^{\frac{1}{m}}$ (Sersic 1968, CCD93) law affects the value of T at the level of $\sim$15%, which is within the uncertainties introduced by the other assumptions (see BLF92). However, since m correlates with r_e (CCD93), this could have a non-negligible effect on the scaling laws. This problem will be analyzed in a forthcoming paper.

The 'intrinsic' rotation curves and velocity dispersion profiles were computed by 'deprojecting' the observables for the integration along the line of sight. These quantities were then integrated on the ellipsoidal region having semi-major axis equal to r_e (as given in Table 1). The specific kinetic energies of rotational and random motions were finally derived as $T_V = \frac{1}{2}V^2$ and $T_\sigma = \frac{3}{2}\sigma^2$ (due to the assumption of isotropy).

The FP parameters were computed by an orthogonal fit which minimizes the sum of squares of the distances of the data to the plane of equation $log(r_e) = a \times log(v) + b \times log(I_e) + c$,

Table 1. The sample with the data used for the derivation of the FP. Column (1) gives the identification of the galaxy. Columns (2) to (6) give the data used to derive the FP equation: (2) effective radius in kpc; (3), (4), (5) σ, V, and σ_0 (in km s^{-1}, see text); (6) mean surface brightness within effective radius (in L$_\odot$ pc^{-2}); (7) absolute B-band magnitude. The sources of the data are: (2), (7) Busarello *et al.* 1996; (3), (4) BLF92; (5), (6) BBF92.

Object (1)	r_e (2)	σ (3)	V (4)	σ_0 (5)	I_e (6)	M_B (7)
NGC 596	3.6	144	58	151	239	-20.2
NGC 636	2.4	156	68	156	331	-19.7
NGC 720	4.9	188	35	248	218	-20.4
NGC 821	5.9	179	117	199	114	-20.2
NGC 1052	3.7	171	105	206	229	-19.8
NGC 1395	4.8	218	107	257	204	-20.3
NGC 1407	8.1	239	84	285	114	-21.0
NGC 1549	3.3	204	79	204	263	-19.8
NGC 1600	17.8	263	46	319	85	-22.9
NGC 2974	6.3	169	231	221	194	-20.6
NGC 3087	3.0	201	26	272	446	-20.7
NGC 3379	1.4	192	53	201	549	-19.4
NGC 3557	9.1	213	226	291	251	-22.2
NGC 3613	5.0	213	76	208	309	-21.0
NGC 3640	4.3	171	120	175	295	-20.8
NGC 3818	3.1	139	121	206	208	-19.4
NGC 3904	3.0	199	46	213	398	-20.1
NGC 4125	8.7	211	154	229	165	-21.4
NGC 4278	1.7	213	45	266	363	-18.8
NGC 4291	2.2	251	75	260	501	-20.2
NGC 4365	5.2	248	31	248	169	-20.5
NGC 4374	4.7	263	56	288	301	-21.0
NGC 4387	1.5	98	39	84	301	-18.3
NGC 4406	8.3	201	38	251	138	-21.1
NGC 4472	9.1	275	43	288	173	-21.8
NGC 4473	2.6	190	61	177	524	-20.2
NGC 4478	1.3	139	39	149	707	-19.1
NGC 4486	8.9	269	19	363	144	-21.6
NGC 4551	1.7	108	35	100	263	-18.4
NGC 4564	2.4	124	142	153	346	-19.3
NGC 4621	4.6	204	136	239	257	-20.5
NGC 4660	1.3	162	146	197	812	-19.3
NGC 4697	10.5	177	151	164	173	-21.7
NGC 5322	6.5	248	56	223	295	-21.7
NGC 5638	4.1	138	71	158	194	-20.1
NGC 5846	12.0	211	6	278	79	-21.2
NGC 7562	6.6	260	10	242	208	-21.9
NGC 7619	8.9	179	139	338	154	-22.4
NGC 7785	8.5	221	100	291	165	-22.0
IC 4296	13.2	257	42	323	93	-22.9

where v is the quantity listed in the first column of Table 2. (Throughout the present work we adopt the orthogonal fit, which offers the advantage of treating the variables in a symmetric way.) The other columns of Table 2 give the best fit parameters and the thickness of the plane in distance and in r_e. The coefficient of $log(I_e)$ is constant within the uncertainties ($b \sim 0.9$) in all cases. It is also worth noticing how the FP becomes much thinner (in δ_d) when introducing the kinetic energies in place of σ_0. Fig. 1 shows the FP derived by means of the total kinetic energy.

Table 2. Summary of the FP solutions. The equation is $log(r_e) = a \times log(v) + b \times log(I_e) + c$. (1): dynamical quantity (v) used for the fit; (2), (3), (4): fit parameters a,b and c; (5): standard deviation in distance from the plane ; (6): standard deviation in $log(r_e)$.

v (1)	a (2)	b (3)	c (4)	δ_d (5)	δ_{r_e} (6)
σ_0	1.11 ± 0.2	-0.91 ± 0.1	$+0.21 \pm 0.5$	0.08	0.13
σ	1.53 ± 0.2	-0.92 ± 0.1	-0.67 ± 0.6	0.06	0.13
T	1.68 ± 0.2	-0.89 ± 0.1	-1.23 ± 0.6	0.05	0.12

3. Non-homology in the dynamical structure

We first discuss the role played by rotation. The residuals to the FP (defined as $R = log(r_e) - a\,log(\sigma) - b\,log(I_e) - c$) computed by using σ appear to correlate with the quantity $log(3 + V^2/\sigma^2)$, i.e. the rotational correction to the kinetic energy. The relation between the two quantities is $R \sim 1.1 \pm 0.3 \times log(3 + V^2/\sigma^2)$, with a linear correlation coefficient $r = 0.49$. The 'fast' rotators lie preferably above the FP (with respect to $log(r_e)$). Once the rotation is included in the FP equation, the exponent of the 'kinetic' term v varies from 1.53 to 1.68, and the corresponding correction to β is $\Delta\beta = 0.06$.

All these results are in good agreement with the findings of PS94 and of D'Onofrio *et al.* 1996. Moreover, the value of $\Delta\beta$ derived here coincides, within the uncertainties, with the value found in PS96 ($\Delta\beta = 0.05$).

Thus, the effect of the rotation on the tilting of the FP, although present, is not large. This is not however a surprising result, since the rotation is not expected to play a major role in establishing the structure of E's.

Somehow surprising is instead the large correction to the tilt ($\Delta\beta = 0.25$, $\Delta\gamma = 0.18$) obtained by substituting σ_0 with σ, i.e. when the kinetic energy of random motions is used instead of the central value of the velocity dispersion. This result implies a non-trivial relation between the central velocity dispersion and the kinetic energy or, in other words, a systematic change in the kinetic energy as a function of σ_0.

We are lead to ascribe this result to a substantial non-homology in the velocity structure of the galaxies. If this is the case, the expression of the VT given in Eq. (1) must be corrected by introducing some dependence on the velocity dispersion in the structure 'constant' C. To see what kind of dependence has to be expected, we write the kinetic energy as $T = C(\sigma_0) \times \sigma_0^2$, where a dependence of the structure constant on σ_0 is explicitly assumed. By assuming, as a first approximation, that the tilt of the FP is due only to dynamical structure effects, the equivalence of the FP and the VT leads to $C(\sigma_0) \sim \sigma_0^{-0.4}$, which implies a kinetic energy proportional to $\sigma_0^{1.6}$ instead of σ_0^2.

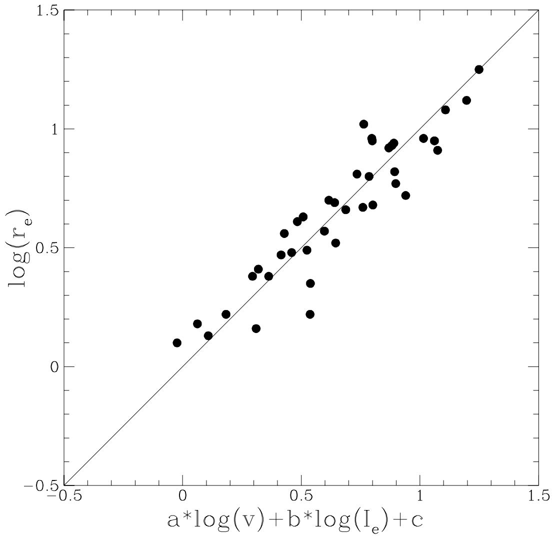

Fig. 1. Edge-on view of the FP computed with the total kinetic energy ($v^2 = 2T$). a=1.68, b=-0.89, c=-1.23.

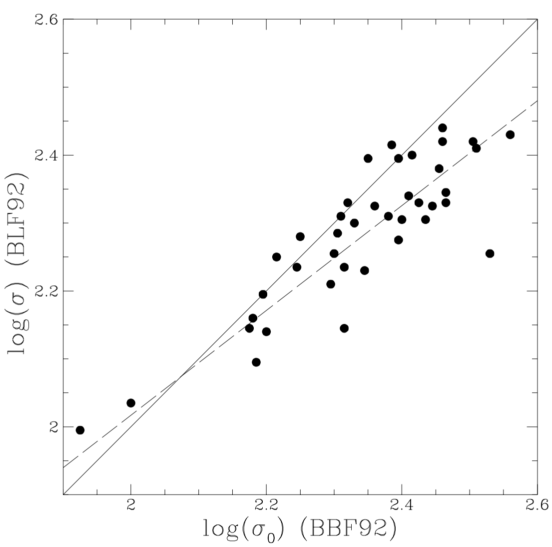

Fig. 2. Relation between σ (BLF92) and σ_0 (BBF92). Continuous line: $\sigma = \sigma_0$; dashed line: the best fit relation ($\sigma = 0.46 \times \sigma_0^{0.78}$).

Fig. 2 shows the relation between σ_0 and σ in the present sample[1]. A trend of σ is apparent in the figure: it increases slower than σ_0. The best fit to the data points (dashed line) gives: $log(\sigma) = 0.78 \times log(\sigma_0) + 0.46$, the linear correlation coefficient being $r = 0.86$.

In agreement with the previous estimate we thus find, for the present sample, $T \sim \sigma_0^{1.56}$. This can be explained if the shape of the velocity dispersion profile changes systematically with σ_0, i.e. with the mass of the galaxy: more massive galaxies have steeper velocity dispersion profiles. We further tested this result by deriving the gradients of the observed velocity dispersion: $\Delta = \sigma_0 - \sigma(r_e/2)$. It turns out that $\Delta \sim 0.48 \times \sigma_0$, with a linear correlation coefficient $r = 0.74$.

[1] Notice that, since σ and σ_0 come from different data sets, in some cases σ, which is a weighted mean of the velocity dispersion, may turn out to be larger than the central value. This has no influence, however, on the present results, which remain the same if σ_0 is derived from the same data as σ.

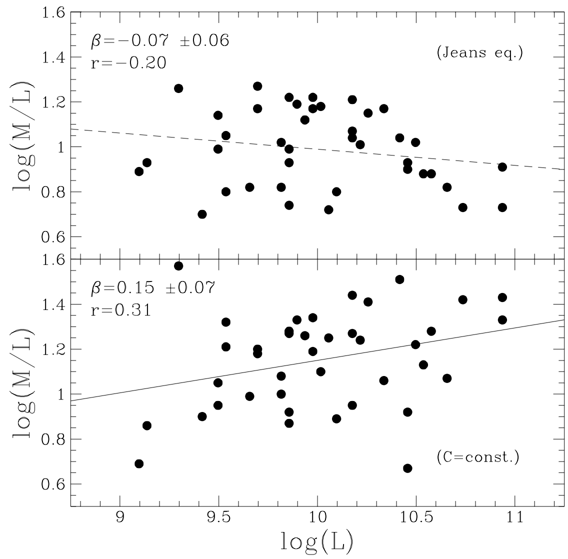

Fig. 3. Mass-to-light ratio vs. luminosity for the 40 galaxies of the present sample in the B waveband and with H_0 = 75 km s^{-1} Kpc^{-1}. Masses are computed by means of the Jeans equation (upper panel), and by means of the virial theorem with the assumption C=const. (lower panel). The values of β are indicated together with the linear correlation coefficient r.

We computed the mass-to-light ratios for the galaxies of the present sample by solving the Jeans equation in the assumption of isotropy and by making use of the spatially deprojected rotation curves and velocity dispersion profiles (Sect. 2, Busarello *et al.*1996). The resulting relation between L and M/L is plotted in the upper panel of Fig. (3).

It is apparent that no real correlation holds between M/L and L. On the other hand, when M/L is computed by applying the VT with C=const. (lower panel), the relation $M/L \sim L^{0.15}$ seems to hold. This apparent contradiction is due to the non-homology in the velocity structure of the galaxies, which leads to overestimating the kinetic energy, (and therefore the mass), of larger galaxies when the central velocity dispersion is used instead of the kinetic energy. We are therefore lead to conclude that the mass-to-light ratio, in the present sample of galaxies, does not depend on the luminosity.

4. Conclusions

We analyzed the possible dynamical contribution to the tilt of the FP in a sample of 40 elliptical galaxies. The FP parameters were derived from (besides the central velocity dispersion) the kinetic energy of random motions and the total kinetic energy (including the rotation).

Table 3. Contributions to the tilt of the FP in terms of the $M/L \sim L^{\beta} I^{\gamma}$ relation and in terms of tilt angle ϕ (see text).

v (1)	β (2)	γ (3)	ϕ (4)	% of tilt (5)	from (6)
σ_0	0.40	0.23	13°		
				55%	dyn. non-h
σ	0.15	0.05	6°		
				15%	rotation
T	0.09	−.03	4°		
				30%	
VT	0	0	0°		

We estimated the relative contributions to the tilt arising from the non-homology in the random motions distribution and from the rotational support. The results are summarized in Table 3 in terms of the $M/L \sim L^{\beta} I_e^{\gamma}$ relation and in terms of the angle ϕ between the FP and the plane defined by the VT. The table gives the values of β and γ (columns 2 and 3) obtained by computing the FP with the kinematical quantity listed in column 1[2]. The last row refers to the values of β and γ predicted by the VT with constant M/L. The fourth and fifth columns of the table give the angle between the FP and the VT plane and the percentage of the tilt due to the effect quoted in the last column.

For what the role of rotation is concerned, our results coincide with the previous analysis by Prugniel & Simien (PS94, PS96): the rotation plays a minor role in the tilt of the FP, since E's are 'pressure-supported' systems. We are also in remarkable agreement with PS96 on the numerical value of the correction to the exponent β coming from the rotation ($\Delta\beta$ = 0.06).

The main result of the present study is that the largest fraction (more than half) of the tilt of the FP comes from a substantial non-homology in the dynamical structure of the galaxies: more massive galaxies turn out to have steeper velocity dispersion profiles, implying that the specific kinetic energy is proportional to $\sigma_0^{1.6}$ rather than to σ_0^2. This could, for instance, arise from a different distribution of dark matter in the inner regions of galaxies having different masses, as envisaged by Ciotti *et al.* (1995), but other explanations are possible.

The dynamical structure of the galaxies accounts for ∼70% of the tilt of the FP. The remaining 30% of the tilt, on the other hand, is well explained by stellar population effects (PS96), and by the effect of the spatial non-homology, which is of the same order as those of the rotational contribution (Prugniel, private communication).

In conclusion, most of the tilt of the FP can be accounted for by the non-homology in the dynamical structure of the galaxies and by the rotational support, or, in other words, that once these effects are properly taken into account, the relation between the 'observables' provided by the FP tends to be equivalent to the relation between the physical quantities provided by the VT, and vice-versa.

The present results suggest that the fundamental plane is a proof that elliptical galaxies are in virial equilibrium and that the 'tilt' between the FP and the VT mainly comes from 'systematic' changes in the relations between the observed ('local') quantities and the corresponding ('global') physical quantities. A conclusion which is remarkably (but not surprisingly) similar to that derived by Djorgovski (1995) for the FP of globular clusters. These arguments also constrain the use of the FP as a distance indicator, which relies on the assumption of the applicability of the same relation to different clusters (e.g. D'Onofrio *et al.* 1996 and references therein). We have shown, on the other hand, that the position of the FP in the space of observables is strongly influenced by the dynamical non-homology of galaxies . Whatever the nature of the non-homology, it should be related to the formation and to the evolution of the galaxies in their own environment. It is likely, for example, that the relation of the kinetic energy to σ_0 depends on the overall properties of the cluster in which the galaxies formed and evolved.

If this is the case, the FP equations relative to different clusters would not depend on their relative distances only, but also on the cluster properties, thus preventing them to be used as distance indicators without a careful consideration of the environmental effects.

It is therefore urgent to investigate the relationships existing between the widely used 'local' properties (like, e.g., σ_0) and the 'global' properties (like, e.g., σ) of elliptical galaxies belonging to different clusters. In this respect, systematic differences in the FP equation seem to exist from cluster to cluster (e.g. Joergensen *et al.* 1996). Such a study could perhaps guide towards an 'environmental correction' (if any) to the FP equation, that could account at least for local non-homology effects in distance determinations.

The next step in the analysis of the dynamical non-homology is to include, in a self-consistent way, the spatial non-homology in the computation of the kinetic energies. The results will be presented in a forthcoming paper.

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[2] Notice that β and γ are derived here from the coefficients a and b defined in Eq. (2), which generally gives values different from those obtainable directly by fitting the FP with absolute magnitudes in place of effective radii (as is done, for instance, in PS96).

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