The M/L vs M Relation and the Tilt of the Fundamental Plane

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ABSTRACT. By making use of extended kinematical data for a sample of ellipticals, we address the problem of the claimed existence of a relation between mass and mass-to-light ratio. We show that dynamical non-homology is largely responsible for that relation.

1. Introduction

The ongoing debate about the existence of a relation between the mass-to-light ratio and the mass or the luminosity of elliptical galaxies originates from the problem of the so-called 'tilt' of the Fundamental Plane (FP), i.e. from the discrepancy between the actual slope of the FP and that predicted by the Virial Theorem (e.g. Djorgovski 1993). When written in terms of the effective radius r_e , the central velocity dispersion σ_0 and the average surface brightness inside the effective radius, I_e , the FP is given by

$$log(r_e) \sim a \times log(\sigma_0) + b \times log(I_e) \quad , \tag{1}$$

where a and b depend on the assumed photometric passband, on the sample and on the adopted fitting procedure (e.g. Busarello et al. 1997, B97). 'Typical' values in the B band are $a \sim 1.4$ and $b \sim -0.8$.

The Virial Theorem (VT), on the other hand, relates the potential energy to the kinetic energy, which are 'global' quantities, i.e. quantities describing a gravitating system as a whole. For homologous systems (i.e. for systems with similar structures) it is possible, by definition, to establish simple scaling relations between local values of physical quantities and the corresponding global properties. In the case of ellipticals, for instance, the total (specific) kinetic energy T would scale with the central velocity dispersion as $T \sim \sigma_0^2$. In the assumption of homology, the VT can thus be written:

$$r_e \sim \sigma_0^2 I_e^{-1} \left(\frac{M}{L}\right)_{hom}^{-1}$$

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Ident.	$\frac{M}{10^{10}M\odot}$	$\frac{M}{L}$	$\frac{M_{hom}}{10^{10}M\odot}$	$\left(\frac{M}{L}\right)_{hom}$	Ident.	$\frac{M}{10^{10}M\odot}$	$\frac{M}{L}$	$\frac{M_{hom}}{10^{10}M\odot}$	$\left(\frac{M}{L}\right)_{hom}$
NGC 596	4.9	5	5.1	6	NGC 3904	8.5	10	8.5	9
NGC 636	3.6	6	3.6	7	NGC 4125	38.0	14	28.2	8
NGC 720	13.5	13	18.6	13	NGC 4278	4.5	18	7.2	28
NGC 821	14.5	16	14.5	14	NGC 4291	8.7	9	9.3	14
NGC 1052	11.2	18	9.8	11	NGC 4365	19.5	16	20.0	16
NGC 1336	1.0	15	1.4	12	NGC 4374	20.4	11	24.0	14
NGC 1339	1.7	13	1.4	6	NGC 4387	1.2	7	0.6	3
NGC 1351	3.5	17	1.9	6	NGC 4406	21.9	10	32.4	13
NGC 1373	0.4	10	0.3	8	NGC 4472	40.7	10	46.8	12
NGC 1374	2.7	9	3.0	9	NGC 4473	7.4	8	5.0	5
NGC 1379	1.5	6	1.6	6	NGC 4478	1.6	5	1.7	5
NGC 1395	15.5	15	19.5	16	NGC 4486	35.5	10	72.4	24
NGC 1404	7.9	10	7.4	8	NGC 4551	1.4	8	1.0	5
NGC 1407	30.2	16	40.7	20	NGC 4564	5.2	13	3.5	6
NGC 1419	0.8	12	0.7	10	NGC 4621	16.2	14	16.2	11
NGC 1427	6.2	19	5.6	12	NGC 4660	3.7	9	3.2	8
NGC 1549	8.7	14	8.5	11	NGC 4697	28.8	8	17.4	3
NGC 1600	85.1	8	112.2	16	NGC 5322	26.9	7	20.0	6
NGC 2974	19.5	15	19.1	9	NGC 5638	5.4	6	6.3	7
NGC 3087	7.2	5	13.5	13	NGC 5846	29.5	14	57.5	19
NGC 3379	2.6	6	3.6	12	NGC 7562	30.9	7	24.0	10
NGC 3557	35.5	6	47.9	8	NGC 7619	35.5	5	63.1	19
NGC 3613	20.0	10	13.5	6	NGC 7785	35.5	7	44.7	14
NGC 3640	9.5	6	8.1	5	IC 4296	57.5	5	85.1	20
NGC 3818	4.7	11	8.1	15					

Tab. 1 - Masses and mass-to-light ratios derived by the Jeans equation (M/L), and by the Virial Theorem $((M/L)_{hom})$ with the assumption of homology.

which, when combined with Eq.1, implies a relation between M/L, mass and surface brightness:

$$\left(\frac{M}{L}\right)_{hom} \sim M^{\beta}_{hom} I^{\gamma}_{e} \quad , \tag{2}$$

where

$$eta = rac{2-a}{2+a} \quad and \quad \gamma = -\left(1+rac{4b}{2+a}
ight) \quad .$$

Since the value of γ is nearly zero for most FP determinations, Eq. 2 is in practice a relation between mass-to-light ratio and mass, or, equivalently, between M/L and luminosity (hence $M/L \sim L^{\beta'}$, where $\beta' = (2 - a)/2a$). For a = 1.4, Eq. 2 gives $(M/L)_{hom} \sim M_{hom}^{0.18}$.

A convincing theoretical explanation for the existence of such a relation that is capable to account for the 'tightness' of the FP is however still lacking (Ciotti et al. 1996). Moreover, elliptical galaxies do not constitute a class of homologous systems (Caon et al. 1993; Djorgovski 1993; Michard and Marchal 1994; B97 and references therein). In the next Section, we study the M/L vs M relation for elliptical galaxies by explicitly taking into account their dynamical non-homology.



Fig. 1. Relation between the masses computed by the Jeans equation and those computed from the VT. Dashed line: least squares fit, continuous line: $M = M_{hom}$.

2. Masses and mass-to-light ratios

The galaxy sample in this study consists in 49 'bona fide' ellipticals having extended $(r \sim r_e)$ stellar kinematical data, fourty of which are taken from B97, while the other nine come from a sample of Fornax ellipticals with new kinematical data (Graham et al. 1997). Kinetic energies and mass-to-light ratios have been derived in the following way.

Galaxies were assumed to be spheroidally-symmetric systems viewed edge-on, thus allowing us to de-project the kinematical and photometric data from line-of-sight integration (see Merritt 1997).

Spatial rotation curves and velocity dispersion profiles were then used to derive the kinetic energies inside one effective major semi-axis. The de-projected kinematical data were also used to solve the Jeans equation in order to obtain the masses and hence the mass-to-light ratios. Besides the assumptions on the spheroidal symmetry of the light/mass distribution and of the orientation with respect to the line-of-sight, other assumptions involved in the derivations are the isotropy of the velocity distribution and the cylindrical symmetry for the velocity field.

All these assumptions are clearly questionable, but they are unavoidable if we want to invert the observed kinematics (Merritt 1997) and compute the global physical properties. The details of the present derivation are given in Lanzoni et al. (1997).

Table 1 gives the values of the masses and of the mass-to-light ratios derived by the method outlined above (columns 2 and 3), and from the VT in the assumption of homology (columns 4 and 5). In the last case $M_{hom} \sim \sigma_0^2 r_e$ (see Mathews 1988 and references therein) and $L \sim r_e^2 I_e$, so that $(M/L)_{hom} \sim \sigma_0^2 r_e^{-1} I_e^{-1}$.

The masses M derived from the Jeans equation and those derived from the VT turn

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Fig. 2. Edge-on view of the FP for the present sample of 49 ellipticals.



Fig. 3. The correlation between mass and mass-to-light ratio, as determined from the VT in the assumption of homology.

out to be related by $M \sim M_{hom}^{0.89\pm.03}$ (see Fig. 1). This shows that the assumption of homology leads to over-estimating the masses of the larger galaxies with respect to those of the smaller ones. The reason for this discrepancy can be found in the dynamical nonhomology of elliptical galaxies: systems having larger σ_0 (and then larger mass) tend to have steeper velocity dispersion profiles (B97). Therefore, a computation based on σ_0 only leads to a systematic overestimate of the masses of larger galaxies.

Figure 2 shows an 'edge-on' view of the FP. The values of the coefficients are $a = 1.33 \pm 0.14$ and $b = -0.76 \pm 0.07$, while the scatter in $log(r_e)$ is 0.14. From Eq. 2 we expect $(M/L)_{hom} \sim M_{hom}^{0.20}$ (the exponent of I_e being γ =-0.09) and, indeed, we find

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Fig. 4. Same as Fig. 3 but with the quantities derived from application of the Jeans equation to the measured photometric and kinematical profiles of the galaxies, and relaxing the assumption of homology.

 $(M/L)_{hom} \sim M_{hom}^{0.20\pm.04}$ (Fig. 3), with a correlation significant at the 99.5% level.

The masses and mass-to-light ratios derived from the Jeans equation are plotted in Fig. 4, which makes evident that the two quantities are no longer correlated. As outlined above, the adopted derivation accounts for the overall kinematical and photometric properties of the individual objects. In other words, the derivation of M and M/L includes all the available information instead of relying on a single, locally measured, value, such as the central velocity dispersion.

The difference in the results obtained from these two approaches is a clear evidence for non-homology: the local properties are not fully representative of the global properties. In the present case, the central velocity dispersion is not fully representative of the kinetic energy.

To further stress this point, we re-derived the FP using the total specific kinetic energy (including the rotational contribution) in place of σ_0 (Fig. 5). Once this 'correction' is applied, the slope coefficients of the FP become: $a = 2.04 \pm 0.23$ and $b = -0.79 \pm 0.08$, while the scatter in $log(r_e)$ is (slightly) reduced to 0.11. Although the exact coincidence of the first coefficient with the prediction of the VT is probably a numerical coincidence, it is a matter of fact that the introduction of quantities that better account for the dynamical non-homology leads to a considerable reduction of the tilt of the FP (see also Prugniel and Simien 1984, 1986; Graham and Colless 1997; B97).

3. Summary and final remarks

The present study shows that a correlation between mass and mass-to-light ratio arises when one forces elliptical galaxies to be dynamically homologous systems. When the observed non-homology is accounted for by a proper derivation of the involved quantities,

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Fig. 5. Edge-on view of the FP computed by using the total kinetic energy (rotation included) in place of σ_0 .

mass and mass-to-light ratio are no correlated, and the tilt of the FP is consistently reduced. This in turn suggests that the FP could constitute the observational evidence that elliptical galaxies are virialized systems.

In the scenario discussed in this paper, the not yet solved problems connected to the existence of a correlation between mass and mass-to-light ratio are, at least in their present formulation, removed.

On the other hand, the same scenario raises the question of the nature of the structural and dynamical non-homology found in elliptical galaxies.

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DISCUSSION

Macchetto. You showed that T vs σ_0 goes like ~ 1.7. Richstone, Tremaine, Kormenet al. (1997) find a direct correlation between masses of central black-holes and mass parent galaxy. Is this in discrepancy with your result?

Busarello. The poportionality between the mass of the central black hole and that the parent galaxy, based on AGN's energetics arguments and on direct mass estimat for local central black holes, is actually assuming the work that you mentioned (Fabet al. AJ 114, 1771). On the other hand, in the same work it is also concluded that the existence of a well defined "core fundamental plane" shows that the mass of th central black hole does not dominate the core potential, although it can distort both th phtometric profile and the central velocity dispersion. If most Es host central massiv black holes, and if its mass is related to the mass of the host galaxy, then what we ca "dynamical non-homology" could be, at least in part, a direct consequence of this.

Arnaboldi. Are you saying that if we use "volume quantities", instead of projecte quantities, i.e. kinematic energy instead of σ_0 , we approach the virial theorem relations

Busarello. Since the virial theorem relates global quantities while the FP relate local quantities, we could not expect a priori that the two relations agree. Our result indicate that the slope of the FP approaches the VT as long as "less local" quantitie are adopted. We are not saying, however, that non-homology accounts for the whole ti of the FP.