SCALING RELATIONS IN DISSIPATIONLESS SPIRAL-LIKE GALAXY MERGERS

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Received 2008 August 23; accepted 2009 April 23; published 2009 June 5

ABSTRACT

We determine both representations of the Fundamental Plane [FP; \( R_e \propto \sigma^2_e (I_f)^{-b} \) and \( R_e \propto (\sigma_v^2 (I_f)^{-b}) \)] and the luminosity-effective phase-space density \( (L \propto f_e^{-\gamma}) \) scaling relation for N-body remnants of binary mergers of spiral-like galaxies. The main set of merger simulations involves a mass ratio of the progenitors in the range of about 1:1 to 1:5, harboring or not a bulge-like component, and are constructed using a cosmological motivated model. Equal-mass mergers are also considered. Remnants lead to average values for the scaling indices of \((a) \approx 1.6, (b) \approx 0.6, (\lambda) \approx 0.7, \) and \((\gamma) \approx 0.65\). These values are consistent with those of K-band observations of ellipticals: \((a) \approx 1.5, (b) \approx 0.8, (\lambda) \approx 0.7, \) and \((\gamma) \approx 0.60\). The b index is, however, not well reproduced. This study does not allow us to establish a conclusive preference for models with or without a bulge as progenitors. Our results indicate that the \( L-f_e \) and FP scalings might be determined to a large extent by dissipationless processes, a result that appears to be in contradiction to other dissipationless results.

Key words: galaxies: kinematics and dynamics – galaxies: structure – methods: N-body simulations – methods: numerical

Online-only material: color figures

1. INTRODUCTION

A large set of observational (e.g., Schweizer 1998; Struck 2006; Rothenberg & Joseph 2004, 2006) and theoretical (e.g., Barnes 1998; Naab & Burkert 2003; Burkert & Naab 2003; Naab et al. 2006) evidence shows that elliptical galaxies are consistent with the picture of being formed by mergers of spiral galaxies (Toomre 1977). However, some matters are still open to discussion, such as the problem of stellar ages and metallicities (e.g., Peebles 2002; Renzini 2006; Naab & Ostriker 2009).

Observationally, one global scaling relation displayed by ellipticals is the Fundamental Plane (FP; Djorgovski & Davis 1987; Dressler et al. 1987), a linear–log relation among the effective radius \( R_e \), the central stellar l-1-dimensional velocity dispersion \( \sigma_0 \), and the mean effective surface brightness \( (I_f)_e \); \( R_e \propto \sigma_0^a (I_f)_e^b \). Values of \( a \) and \( b \) depend on several factors among the most important are: (1) the observed wavelength; (2) the fitting method; (3) the assumed underlying light profile in early-type galaxies; and (4) the width and brightness of the magnitude range of the sample (e.g., Jørgensen et al. 1996; Papageorgiou et al. 1998; Mobasher et al. 1999 (MGZ99); Bernardi et al. 2003 (B03); Jun & Im 2008; D’Onofrio et al. 2008; La Barbera et al. 2008; Nigoche-Neto et al. 2009). A wide range of values \( a \approx (1–2) \) and \( b \approx (0.5–1) \) can be found in the diverse cited works.

If structural and kinematical homology is assumed, as well as a constant mass-to-light ratio, direct application of the physical virial theorem to observational related quantities leads to a FP with coefficients \((a, b) = (2, 1)\). The discrepancy of these values with the observed ones is usually termed as the “tilt” of the FP; see also (4).

The overall features of the observed FP are reproduced by merger studies (e.g., González-García & van Albada 2003; Aceves & Velázquez 2005 (AV05); Boylan-Kolchin et al. 2005; Robertson et al. 2006 (R06); Dekel & Cox 2006), but all show differences in values obtained for the indices \( a \) and \( b \) depending on the details of the initial conditions (e.g., the presence or not of a bulge and/or a gas component) used in the simulations. It is likely that a combination of broken structural and dynamical homology and stellar population effects, along with a variation of the central mass-to-light ratio, may lead to the explanation of the tilt (e.g., Scodellaggio et al. 1998; Trujillo et al. 2004, AV05; Riccicuti et al. 2005, R06; Bolton et al. 2007; Jun & Im 2008).

The study of La Barbera et al. (2008) points in the direction that the tilt of the FP is not driven by stellar populations but from other processes like a homology breaking. They derive tight values of \( a \approx 1.5 \) and \( b \approx 0.75 \) from a large sample of early-type galaxies by combining Sloan Digital Sky Survey (SDSS) and UKIDSS data in the optical and near-infrared (NIR). However, D’Onofrio et al. (2008) found larger variances of the distributions of the FP coefficients as derived from a sample of three larger surveys (WINGS, NFPs, and SDSS) suggesting that a such wide range of values for \( a \) and \( b \) seems to be in contradiction with the idea of a universal FP relation and speculate that the FP corresponds to a bent surface.

The importance of dissipative processes in the merger hypothesis was recognized early from estimates of the central physical phase-space density of ellipticals, which turned out to be higher than that of spirals (e.g., Ostriker 1980; Carlberg 1986; Gunn 1987; Lake 1989; Kormendy 1989). In a dissipationless scenario of galaxy merging, Liouville’s theorem (e.g., Binney & Tremaine 1987) demands that the central physical phase-space density remains constant so, given the previous observational estimates, it prohibits a dissipationless picture of merging disk galaxies to form ellipticals. Robertson et al. (2006) using a large set of simulations of equal-mass mergers (eMs) without and with a gas component, and other physical processes, conclude that the FP in the K band (Pahre et al. 1998) and the effective radius–stellar mass scaling relation \( (R_e M_s) \) (Shen et al. 2003 (S03)) can only be reproduced by mergers of disk galaxies with a gas fraction \( f_{gas} > 30\% \) with respect to the mass of the disk component, \( M_d \); ruling out dissipationless mergers as mechanism to produce these two global scaling relations. Cox et al.

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(2006) also found that $f_{\text{gas}}$ is of the same order to reproduce the kinematic properties of ellipticals.

Obtaining higher central phase densities in models of elliptical galaxy formation can be achieved, aside of taking into account dissipational processes, by including a bulge-like component in the progenitors (e.g., Vedel & Sommer-Larsen 1990; Hernquist et al. 1993; hereafter HSH). This result is in agreement with several N-body simulations that have found that mergers of pure disk galaxies, residing inside dark halos with a core-like profile, are not able to reproduce the surface brightness density profiles typically found in ellipticals (e.g., González-García & Balcells 2005; Naab & Trujillo 2006).

The combination of arguments based on the non-reproducibility of the FP, the estimates of phase-space densities, and the density profiles obtained from diverse N-body simulations have lead to the idea that collisionless models of disk galaxies, with or without a bulge, are ruled out as viable progenitors to form ellipticals (e.g., Carlberg 1986; HSH; Mao & Mo 1998; R06; Oiohrbe et al. 2006; Robertson et al. 2006). Nonetheless, there are results of N-body mergers of pure disk galaxies residing in cuspy dark halos that lead to density profiles consistent with those of early-type galaxies (Aceves et al. 2006: AVC06) and are able to reproduce adequately the Fundamental Plane scaling relation (AV05). Our results of dissipationless mergers (see below) suggest that they cannot be ruled out on the basis of scaling arguments.

On the relevance of a bulge-like component in progenitors of merger remnants, there is observational evidence that an important fraction of spirals does not harbor a bulge-like structure, or that it does not have a significant contribution, as is the case of late type morphological Hubble types usually called “flat galaxies” (e.g., Goad & Roberts 1981; Karachentsev 1989; Kautsch et al., 2006; Domínguez-Palmero et al. 2008). According to the sample considered by Kautsch et al., about one third of spirals are flat galaxies or simple disks, and in the sample of Domínguez-Palmero et al. about 30% (54) harbor a bulge and about 70% (137) have no measurable bulge. Thus, these flat galaxies arise the immediate issue about to what extent N-body simulations are able to establish global scaling relations like the FP when merging.

Undoubtedly, an important test on the details of the merger hypothesis is imposed by the phase-space constraints. A comparison among theoretical models of the central physical phase-space density, $f_p$, using different models and initial conditions, although important for our understanding of the structure of remnants, needs to be related to observations in order to determine their relevance. Different works have already shown that $f_p$ increases with the inclusion of a dissipative process (e.g., R06) or a bulge inside a core-like halo (e.g., Naab & Trujillo 2006). However, given that the physical central phase-space density, $f_p$, cannot be determined observationally an estimator has to be used when comparing with observations.

An early estimator was the core coarse-grained phase-space density, $f_c$, proposed by Carlberg (1986). However, HSH considered that a more robust one is the effective coarse-grained phase-space density, $f_e$. A strong dependency of $f_e$ with the luminosity, $L$, of ellipticals has been found in several works (e.g., Carlberg 1986; Lake 1989; HSH; Mao & Mo 1998). For example, using data of Bender et al. (1992), HSH found that $L_B \propto f_e^{0.54}$ for the compact, intermediate and giant ellipticals with an rms scatter of 0.15 mag; with $L_B$ being the total luminosity in the B band.

The FP and $L-f_e$ scaling relations appear to be tight enough to serve as constraints for the formation scenario of elliptical galaxies. However, it should be said that up to now there is no direct comparison of the $L-f_e$ scaling relation obtained from observations with its counterpart provided by the remnants of merger simulations. Previous works (e.g., HSH; RO6) have computed only the physical cumulative coarse-grained distribution function, $s(f)$, which is compared with a model of an elliptical galaxy or either with the effect of introducing a bulge and/or gas component in the progenitors, but it has not been related with an observational quantity.

By restricting the comparison of our numerical remnants with infrared observations, for which stellar population age effects are minimum (e.g., Bruzual & Charlot 2003), and by adopting a procedure similar to the one used in observational studies, we examine to what extent N-body numerical simulations of spiral-like galaxy mergers, with or without a bulge-like component, are able to reproduce the observed $L-f_e$, the FP and the $R-M$ global relations. The latter two results are compared with those obtained in our earlier works (AV05; AVC06) where the progenitor galaxies lacked a bulge component and with recent results from other authors.

It is important to mention that we do not attempt to determine the “zero point” of the above scaling relations since this surely requires to include more physical processes, such as star formation, cooling, and feedback among others; a matter that is out of the scope of the present work.

This paper has been organized as follows. In Section 2, we summarize the numerical galaxy models and tools used to carry out this work. Section 3 presents our results and Section 4 contains a discussion and final comments.

2. SIMULATIONS

The method to build up our galaxy models is described in AV05 and for the sake of clarity it is briefly summarized. The galaxy models considered here satisfy the Tully–Fisher relation (Tully & Fisher 1977). They are set up by combining the Press–Schechter formalism of hierarchical clustering and the cosmologically motivated model of disk galaxy formation of Mo et al. (1998, MMW). Essentially the method outlined by Shen et al. (2002) is followed. In this scenario a formation redshift for disks needs to be established, which was set here to be $z = 1$ corresponding to a look-back time of $\approx 8$ Gyr (Peebles 1993); simulations with disks formed at higher $z$ were not considered. In the MMW model, disks at higher redshifts are smaller and denser than those at the present cosmic epoch. A $\Lambda$CDM cosmological model with $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$ and a Hubble parameter $h = 0.7$ is adopted. The numerical progenitors satisfy the disk stability criteria of Efstathiou et al. (1982), $v_{\text{circ}}^2/(GR_d^{-1}M_d) > 1.0$ where $v_{\text{circ}}$, $R_d$ and $M_d$ are the maximum rotational velocity, the radial scale length and the total mass of the disk.

The N-body galaxy models consist of a spherical dark halo, a stellar disk and a bulge component. The dark halo follows a Navarro et al. (1997) profile with an exponential cutoff. The disk component has an exponentially decaying radial density profile and an isothermal vertical structure. Finally, the bulge-like component is represented by a spherical Hernquist profile (Hernquist 1990). The bulge in this galaxy formation scenario is introduced by following the procedure described by Springel & White (1999). In all cases, a fixed mass fraction of 0.25$M_d$ and a scale length of one-third of the radial scale
of the disk are adopted for the bulge. Table 1 summarizes the parameters of our progenitor galaxies with a central bulge component.

Also, for comparison purposes the remnants of our pure disk galaxy models described in AV05 together with five new similar merger simulations are included. In this case, the progenitors of those galaxies partaking in mergers M01, M05, M07, M08, and M10 of AV05 that lead to luminous-dominated merger cores. New orbital parameters, following the above procedure, were obtained.

Simulations were done using the parallel tree-based code GADGET-2 (Springel et al. 2001; Springel 2005). They were evolved for about 8 Gyr, a time similar to the time spanned from $z = 1$ to the present epoch and at which the remnants had reached equilibrium. Softening for disk, bulge and halo particles were taken to be $\epsilon_d = \epsilon_b = 35$ pc and $\epsilon_h = 350$ pc, respectively, with a parameter $Err Tol Force Acc= 0.0025$. Energy conservation was better than 0.75% in all simulations.

### 3. RESULTS

In this section, we present the FP, $R_e - M_*$, and the $L - f_e$ relations for our dissipationless mergers of spiral-like galaxies.

We resort to a procedure similar to that used in practice with the observations in order to avoid, as far as possible, any kind of biases in our results making difficult their comparison with them. K-band observations are better suited for our purposes, since they are less affected by stellar population effects. For this reason we have chosen the observational data of MGAZ99 which are publicly available.
The results for bulgeless progenitors are obtained by considering only those mergers of our sample (10 out of 15) that resulted in remnants dominated by “luminous” matter inside their effective radius \( R \lesssim R_e \approx 1–2 \) kpc as suggested by observations (e.g., Gerhard et al. 2001; Thomas et al. 2007). However, the scaling indices do not change significantly if remnants centrally dominated by dark matter are included.

Each remnant was “observed” along 100 random different lines of sight and fitted with a \( R^{1/4} \) profile (de Vaucouleurs 1953) and a Sérsic profile (Sérsic 1968). The \( R^{1/4} \) profile was adopted to compare directly with MGAZ99 while the Sérsic profile is better suited to fit our numerical remnants and it is characterized by the following surface density:

\[
\Sigma(R) = \Sigma_0 \exp \left[-\left(\frac{R}{R_e}\right)^{1/n}\right], \tag{1}
\]

where \( b = b(n) \approx 2n - 1/3 + 4/(405n) \) (e.g., Graham & Driver 2005), \( \Sigma_0 \) is the central projected surface luminosity mass density, and \( n \) is the corresponding Sérsic index. The radial interval of the fit is taken from our numerical resolution value for the luminous matter (2.86\( R_e = 2.86\) kpc) to the outer radius enclosing 95% of the projected luminous mass, determined directly by counting particles from the simulations. The parameters \( \Sigma_0 \), \( R_e \), and \( n \) of the profile were found by a \( \chi^2 \)-minimization using the Levenberg–Marquardt method (e.g., Press et al. 1992).

The total luminous mass of a Sérsic model is given by

\[
M_L = \frac{2\pi n}{b^{2n}} \Gamma(2n) \Sigma_0 R_e^{2n}, \tag{2}
\]

were \( \Gamma \) is the Gamma function. For a crude estimate of the luminosity, \( L_\odot \), of the numerical remnants we may choose a constant stellar mass-to-light ratio, \( \Upsilon_\odot \), leading to \( L = \Upsilon_\odot^{-1} M_L \).

To estimate a total magnitude \( M_K \) in the \( K \) band we take as a fiducial values \( \Upsilon_\odot = 0.97 \), in solar units, and \( M_\odot = 3.32 \).

The central projected, luminosity weighted, velocity dispersion, \( \sigma_0 \), of the luminous particles was computed inside a circular region of radius \( R_e/8 \) for each remnant projection, as is usually done in observational studies (e.g., Jørgensen et al. 1996; MGAZ99; D’Onofrio et al. 2008). A value for the mean effective surface brightness \( \langle I \rangle_e \) can be obtained from the fitted parameters of the profile and by assuming a constant \( \Upsilon_\odot \). Results of different quantities for our set of simulations with bulge progenitors are shown in Table 2.

### 3.1. Fundamental Plane

A log plane of the form

\[
\log R_e \propto a \log \sigma_0 + b \log \langle I \rangle_e \tag{3}
\]
was fitted to our remnant values by two standard methods (e.g., B03): the direct least-square method (LSQ) and an orthogonal plane (ORT) procedure. The tilt $\lambda$ of the FP given by

$$\log R_e \propto \lambda \log \left( \frac{\sigma_v^2}{I_e} \right),$$

was also determined using the two previous fitting methods. Both the LSQ and ORT methods were tested against synthetic data, in two and three dimensions, with excellent agreement between the synthetic and fitted parameters.

Table 3 summarizes the main results for our simulations with and without a bulge component, and using either a Sérsic (S) or $R^{1/4}$ profile. Columns (3–5) provide the indices $a$ and $b$ along with the corresponding rms. Column (6) provides the tilt ($\lambda$) of the FP, and Column (7) shows the index $\mu$ for the fitting of the relation $R \propto M_{e}^{\mu}$. Column (8) presents the index $\gamma$ of the luminosity–phase space relation (see below), and Column (9) indicates the fitting method used. We have also included results for a set of simulations of eMs lacking a bulge component. Errors in the ORT fits were estimated by bootstrap, while those in the LSQ fits is the standard rms.

For comparison purposes, we have included the following in Table 3. (1) Values quoted by Robertson et al. (2006) for their $N$-body and full ($N$-body+gas) simulations were included. The methodology followed by these authors is, however, different to the one adopted here and in observational studies. Robertson et al. directly measure a half-mass stellar effective radius ($R_{50}$) inside which the one-dimensional dispersion velocity, $\sigma_0$, and a mean surface density $I_e = M_{e,50}(< R_{50})/\pi R_{50}^2$ are determined; a three-dimensional log plane (3) is then fitted by an LSQ method. (2) Some fits from observational data are also included.

Data from MGAZ99 for Coma ellipticals are used to compute different scalings. We indicate Bahre et al. (1998), PdC08 average fitted parameters for the FP for all the clusters in their sample as well as the corresponding ones to the Coma cluster. The FP in the $K$ band from La Barbera et al. (2008, LaB08) is also shown. Despite the SDSS data are in the optical region, we include the FP and $R$-$M_e$ relations derived by Bernardi et al. (2003) and Shen et al. (2003) using an $R^{1/4}$-LSQ–ORT and a Sérsic–ORT profile, respectively.

In Figure 1, we plot the FP in the “virial plane” representation: $R_e - \sigma_v^2/I_e^{-1}$. Here, results from our $N$-body mergers, with (solid dots) and without (filled triangles) a bulge-like component, are shown. eMs lacking a bulge are also included (open stars). For comparison, the FP in the $K$ band is represented by open squares and, finally, the tilt, $\lambda$, in each case is provided.

From Table 3, it follows that our $N$-body remnants show different values for the indices $a$, $b$, $\lambda$, and $\mu$, depending on both the fitting method and the assumed profile for the luminous matter. Averaging over all the results, ignoring the details of the fitting, lead to $\langle a \rangle \approx 1.6$, $\langle b \rangle \approx -0.6$, $\langle \lambda \rangle \approx 0.7$, and $\langle \mu \rangle \approx 0.5$. On the other hand, the corresponding $K$-band averages are: $\langle a \rangle \approx 1.5$, $\langle b \rangle \approx -0.8$, $\langle \lambda \rangle \approx 0.7$, and $\langle \mu \rangle \approx 0.6$.

The previous average values indicate general good agreement between the theoretical and observational values; they are also consistent with those obtained by Bolton et al. (2007) using lens galaxies: $a = 1.50 \pm 0.32$ and $b = -0.78 \pm 0.13$. However the index $b$, associated with the luminosity and not the stellar mass, is the one that shows a larger discrepancy from the observed values. A similar thing occurs for the $\mu$ index. Nonetheless the tilt, $\lambda$, obtained through the fit of the combined variable $\sigma_0/I_e$, yields results that agree very well with the observational data.

Judging only from the individual indices $a$ and $b$ it is not clear if models of progenitors with or without a primordial bulge are to be preferred, although progenitors without a bulge and different mass ratios appear to be favored when the tilt $\lambda$ is estimated.

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3 Formulae (9) and (14) in Robertson et al. (2006) for the direct least-squares method display two misprints; compare them with Bernardi et al. (2003).
3.2. Luminosity–Phase Space Relation

The effective coarse-grained phase-space density of our numerical remnants is computed using Equation (2.12) of HSH for the luminous matter, namely

$$ f_e \equiv \frac{1}{a_0 R_e^2}, $$

where the gravitational constant $G$ has been taken to be unity. This estimator allows a more direct comparison of the global trend of the coarse-grained central phase space with $M_K$ of our numerical remnants with their observational counterparts. A direct least-squares fit of the form

$$ \log L_K \propto -\gamma \log f_e, $$

where $\gamma$ is the fitting parameter, is done to the mean of the values of the projections of each remnant. The magnitude value is taken as $M_K = -2.5 \log L_K$. A similar fit is done to the observational data of MGAZ99.

The correlations $M_K$ vs $f_e$ for our numerical remnants corresponding to progenitors with (solid dots) and without a bulge component (solid triangles) are indicated in Figure 2. Results for the eMs are shown with an open-star symbol. For comparison, the $M_K$ vs $f_e$ relation derived from the data of MGAZ99 is also shown (open squares). The index $\gamma$ obtained for the different cases considered in this work are shown in Table 3.

A scaling relation of the form $L \propto f_e^{-\nu}$ results from these fits, with $\gamma = 0.66$ and $\gamma = 0.51$ for our remnants (using a $R^{1/4}$ profile and LSQ) from progenitors with and without a bulge, respectively. For equal-mass mergers, we have $\gamma = 0.63$.

The value for the MGZA99 sample is $\gamma = 0.57$. This value is similar to that obtained in the $B$ band for the data of Bender et al. (1992) by HSH ($\gamma = 0.54$), and that if we use the ellipticals from D’Onofrio (2001) ($\gamma = 0.51$); despite the fact that D’Onofrio uses a Sérsic profile to fit the brightness distribution while Bender et al. consider a $R^{1/4}$ profile.

In general, good agreement, within uncertainties, among the $N$-body and observed $\gamma$ indices exist. Taken at face value, non-equal mass (bulgeless) mergers have a closer value to the observed ones. However, as for the FP case, our results preclude us from favoring a particular model for the progenitors.

4. DISCUSSION AND FINAL COMMENTS

An important conclusion of recent works on mergers (e.g., R06, Naab & Trujillo 2006; Cox et al. 2006; Dekel & Cox 2006) is that dissipation plays a major role in reproducing different scaling relations; such as the FP or the $R_e-M_*$ relation. In particular, R06 found that the initial fraction of gas in merging galaxies should be $\approx 30\%$ of the disk mass in order to reproduce both the observed scaling of the Fundamental Plane and the $R_e-M_*$ relation.

However, previous works by AV05 and AVC06 were able to reproduce rather adequately these global scaling relations without invoking a gas component or even a bulge-like structure. The $b$ index of the FP was less well reproduced, perhaps due to the assumption of a constant $Y_e$ to obtain $<I>_e$. The results found here for progenitors with a bulge, and bulge-less equal-mass mergers, are in general in same standing when compared with NIR data under methods that mimic the observational procedure.

As mentioned earlier, the observed tilt $\lambda$ is well reproduced in our dissipationless simulations. The reason for this agreement, although the $b$ index is rather poorly matched (see Table 3),
might be related to correlations present among the variables (and their errors) involved in the fitting of the FP. Such correlations will affect the fitting parameters depending on how the FP is fitted, either as in Equation (3) or in (4). On the other hand, it is not clear the origin of the difference between our fitted values of \( a \) and \( b \) of the FP and those derived by Robertson et al. (2006) for their equal-mass dissipationless simulations. For instance, when we use the half-projected stellar mass radius, \( R_{50} \), and the one-dimensional velocity dispersion, \( \sigma_0 \), inside this radius we obtain a value of \( a \approx 1.8 \) that tends to the expected virial value as in R06. However, even in this case our value for \( b \approx 0.5 \) is far from unity (see Table 3). The tilt \( \lambda \approx 0.8 \) in this case tends to increase a little but still it is not unity.

Given our results, the FP appears to arise mainly from broken structural and dynamical homology between the observed (luminous component) quantities \( \{R_5, R_e, (I_e)\} \) and their theoretical counterparts \( \{V^2, R_e, M\} \); where \( V^2 = 2T/M \), \( R_e = GM^2/|U| \), and \( M \) is the total bound mass of the system. Here \( T \) is the total kinetic energy of the system, with contributions from rotational and thermal motion in remnants. An indication of the previous was presented in Aceves & Velázquez (2005b). Variations in the stellar mass-to-light ratio, \( Y_* \), can be responsible for some of the tilt in the FP, especially if we focus on the value of the \( b \) index for our remnants. However, the effect of \( Y_* \) would tend, according to our results, to diminish when the \( \lambda \) parameter is used as an indicator of the FP tilt.

The \( L-f_e \) scalings shown in Figure 2 are in the same direction as the preceding results on the FP, suggesting that the establishment of this scaling relation is consistent with a dissipationless merging scenario. It is likely that dissipative processes (e.g., star formation and feedback) will play a major role in defining the zero point of all these scaling relations, and affect the indices in not a simple way.

From energy arguments in a dissipationless scenario, and assuming equal-mass galaxies, Hernquist et al. (1993) derived the particular relation \( L \propto f_e^{-3.5} \). When non-identical progenitors are taken into account these energy arguments predict a shallower log slope; for example, for a mass ratio of about 1 \( \gamma \) of the for the non-equal mass ratios considered here. Thus, the theoretical expectation on the basis of these energy arguments is about 30% lower than the average value \( \langle \gamma \rangle \approx 0.7 \) for our bulge equal-mass mergers. Meanwhile these theoretical values are more closer to those of our remnants from bulgeless progenitors.

The average result from all of our mergers yields an index \( \langle \gamma \rangle \approx 0.65 \) that is in good agreement with the observed NIR value \( \gamma \approx 0.60 \). This agreement spans for about four magnitudes and compromises remnants that can be cataloged from bright dwarf ellipticals to intermediate early-type galaxies (see Figure 2).

It should be noticed that differences arise when a primordial bulge is considered or not, and merger remnants from bulgeless progenitors tend to produce a scaling more close to the NIR one. In general, for larger “luminosity” the effective phase-space density tends to a higher value for remnants with progenitors having a bulge as is found in works with progenitors with the physical distribution function \( f_p \) (e.g., HSH; Naab & Trujillo 2006; Robertson et al. 2006). At low “luminosity” the behavior of \( f_e \) does not show a clear difference for bulge or bulgeless progenitors.

A physical explanation for the details of the behavior of \( L-f_e \) (or its physical counterpart) is non-existent at the moment, although the arguments of HSH yield light on the subject. On the other hand, unfortunately, the more extended study carried out by R06 did not address the \( L-f_e \) scaling relation to compare directly with our \( N \)-body results.

In summary, the observed \( \lambda \)-tilt of the FP and the \( \gamma \)-index of the luminosity–phase space relation, both in the NIR, are consistent with those obtained here through dissipationless merger simulations; at least over the luminous mass range covered by our remnants. We ascribe such concordance to the use of progenitors constructed under a cosmological motivated model of galaxy formation, with a Navarro–Frenk–White dark halo and satisfying initially a Tully–Fisher relation.

As a concluding remark, given the results of this work, we would like to point out that trying to deduce the amount of primordial gas (\( \rho_{gas} \)) in models of progenitors, taking part in merger events, to satisfy a global scaling relation like the FP, might be subject to a non-negligible uncertainty. It is likely that the zero point of the scaling relations would be a better constraint to the dissipational component of disk galaxy progenitors. In our opinion this is a subject that requires further work, but it is out of the scope of the present work.

This research was funded by UNAM-PAPIIT Research Project IN121406, and CONACYT Project 25030. The simulations presented here were run on KAN BALAM of DGSCA-Departamento de Supercómputo of the Universidad Nacional Autónoma de México, and in the Centro Nacional de Supercómputo de San Luis Potosí.

REFERENCES

Aceves, H., & Velázquez, H. 2005a, MNRAS, 360, 50 (AV05)
Aceves, H., & Velázquez, H. 2005b, RevMexAA, 41, 523
Aceves, H., Velázquez, H., & Cruz, F. 2006, MNRAS, 373, 632 (AVC06)
Barnes, J. E. 1998, in Galaxies: Interactions and Induced Star Formation, Saas-Fee Advance Course 26, ed. D. Friedli, L. Martinet, & D. Pfenniger (New York: Springer), 275
Bender, R., Burstein, D., & Faber, S. M. 1992, ApJ, 399, 462
Bernardi, M., et al. 2003, AJ, 125, 1866
Bolton, A. S., Burles, S., Treu, T., Koopmans, L. V. E., & Moustakas, L. A. 2007, ApJL, 665, L105
Binney, J., & Tremaine, S. 1987, Galactic Dynamics (Princeton, NJ: Princeton Univ. Press)
Boylan-Kolchin, M., Ma, C.-P., & Quataert, E. 2005, MNRAS, 362, 184
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000
Burkert, A., & Naab, T. 2003, in Lecture Notes in Physics 626, Galaxies and Chaos, ed. G. Contopoulos & N. Voglis (Berlin: Springer-Verlag), 327
Carlberg, R. G. 1986, ApJ, 310, 593
Cox, T. J., Dutta, S. N., Di Matteo, T., Hernquist, L., Hopkins, P. F., Robertson, B., & Springel, V. 2006, ApJ, 650, 791
Dekel, A., & Cox, T. 2006, MNRAS, 370, 1445
de Vaucouleurs, G. 1953, MNRAS, 113, 134
Djorgovski, S., & Davis, M. 1987, ApJ, 313, 59
Dominguez-Palmero, L., Balcells, M., Erwin, P., Prieto, M., Cristóbal-Hornillos, D., Eliche-Moral, M. C., & Guzmán, R. 2008, A&A, 488, 1167
D’Onofrio, M. 2001, MNRAS, 326, 1517
D’Onofrio, M., et al. 2008, ApJ, 685, 875
Dressler, A., Lynden Bell, D., Burstein, D., Davies, R. L., Faber, S. M., Terlevich, R. J., & Wegner, G. 1987, ApJ, 313, 42
Efstathiou, G., Lake, G., & Negroponte, J. 1982, MNRAS, 199, 1069
Gerhard, O., Kronawitter, A., Saglia, R. P., & Bender, R. 2001, AJ, 121, 1936
Goad, J. W., & Roberts, M. S. 1981, ApJ, 250, 79
Goldstein, H. 1950, Classical Mechanics (Reading, MA: Addison-Wesley)
González-García, A. C., & van Albada, T. S. 2003, MNRAS, 342, L36
Graham, A. W., & Driver, S. P. 2005, Publ. Astron. Soc. Aust., 22, 118
Gunn, J. E. 1987, in IAU Symp. 127, Structure and Dynamics of Elliptical Galaxies, ed. T. de Zeeuw (Dordrecht: Reidel), 17
Hernquist, L. 1990, ApJ, 356, 359
Hernquist, L., Spergel, D. N., & Heyl, J. S. 1993, ApJ, 416, 415 (HSF)
Jørgensen, I., Franx, M., & Kjærgaard, P. 1996, MNRAS, 280, 167
Jun, H. D., & Im, M. 2008, ApJ, 678, L97
Karachentsev, I. 1989, AJ, 97, 1566
Kautsch, S. J., Grebel, E. K., Barazza, F. D., & Gallagher, J. S., III 2006, A&A, 445, 765
Kormendy, J. 1989, ApJ, 342, L63
La Barbera, F., Busarello, G., Merluzzi, P., de la Rosa, I. G., Coppola, G., & Haines, C. P. 2008, ApJ, 689, 913
Lake, G. 1989, AJ, 97, 1312
Mao, S., & Mo, H. J. 1998, MNRAS, 296, 847
Mo, H. J., Mao, S., & White, S. D. M. 1998, MNRAS, 295, 319 (MMW)
Mobasher, B., Guzman, R., Aragon-Salamanca, A., & Zepf, S. 1999, MNRAS, 304, 225
Naab, T., & Burkert, A. 2003, ApJ, 597, 893
Naab, T., Jesset, R., & Burkert, A. 2006, MNRAS, 372, 839
Naab, T., Khochfar, S., & Burkert, A. 2006, ApJ, 636, L81
Naab, T., & Ostriker, J. P. 2009, ApJ, 690, 1452
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1995, MNRAS, 275, 56
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1997, ApJ, 490, 493
Nigoche-Netro, A., Ruelas-Mayorga, A., & Franco-Balderas, A. 2009, MNRAS, 392, 1060
Otorbe, J., Domínguez-Tenreiro, R., Sáiz, A., Artal, H., & Serna, A. 2006, MNRAS, 373, 503
Ostriker, J. P. 1980, Comments Astrophys., 8, 177
Pahre, M. A., de Carvalho, R. R., & Djorgovski, S. G. 1998, AJ, 116, 1591
Peebles, P. J. E. 1993, Principles of Physical Cosmology (Princeton, NJ: Princeton Univ. Press)

Peebles, P. J. E. 2002, in ASP Conf. Proc. 283, A New Era in Cosmology, ed. N. Metcalfe & T. Shanks (San Francisco, CA: ASP)
Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P. 1992, Numerical Recipes (New York: Cambridge Univ. Press)
Renzini, A. 2006, ARA&A, 44, 141
Ricotti, A., Lanzoni, B., Bonoli, S., & Ciotti, L. 2005, A&A, 443, 133
Robertson, B., Cox, T. J., Hernquist, L., Franx, M., Hopkins, P. F., Martini, P., & Springel, V. 2006, ApJ, 641, 21 (RO6)
Rothberg, B., & Joseph, R. D. 2004, AJ, 128, 2098
Rothberg, B., & Joseph, R. D. 2006, AJ, 131, 185
Schweizer, F. 1998, in Galaxies, Interactions and Induced Star Formation, Saas-Fee Advance Course 26, ed. D. Friedli, L. Martinet, & D. Pfenniger (New York: Springer), 105
Scodelllo, M., Gavazzi, G., Belsole, E., Pierini, D., & Boselli, A. 1998, MN--RAS, 301, 1001
Sérsic, J. L. 1968, Atlas de Galaxias Australes (Córdoba, Argentina: Observatorio Astronómico)
Shen, S., Mo, H. J., & Shu, C. 2002, MNRAS, 331, 251
Shen, S., Mo, H. J., White, S. D. M., Blanton, M., Kauffmann, G., Yoges, W., Brinkmann, J., & Csabai, I. 2003, MNRAS, 343, 978
Springel, V. 2005, MNRAS, 364, 1429
Springel, V., & White, S. D. M. 1999, MNRAS, 307, 162
Springel, V., Yoshida, N., & White, S. D. M. 2001, New Astron., 6, 79
Struck, C. 2006, in Astrophysics Update 2, ed. J. W. Mason (Berlin: Springer-Verlag), 115
Thomas, J., Saglia, R. P., Bender, R., Thomas, D., Gebhardt, K., Magorrian, J., Corsini, E. M., & Wegner, G. 2007, MNRAS, 382, 657
Toomre, A. 1977, in The Evolution of Galaxies and Stellar Populations, ed. B. M. Tinsley & R. B. Larson (New Haven, CT: Yale Univ. Obs.), 401
Trujillo, I., Burkert, A., & Bell, E. F. 2004, ApJ, 600, L39
Tully, R. B., & Fisher, J. R. 1977, A&A, 64, 661
Vedel, H., & Sommer-Larsen, J. 1990, MNRAS, 245, 637
Weil, M. L., & Hernquist, L. 1996, ApJ, 460, 101