Making ellipticals with mergers

Only quite recently have simulations become realistic enough to include gas (and feedback) in merger sim.

- Comparison of mergers with stars only & with significant amounts of gas show different amounts of rotational support in remnants.

- "Fill" of fundamental plane (deviation from predictions of virial theorem) can be reproduced via gas-rich mergers.

- Elliptical galaxies made via gas-rich AND gas-free mergers (dissipationless).
  Most massive ES made via dry (dissipationless) mergers, less massive ones need gas in simulations to reproduce properties.
\( V_{\text{maj}} / \sigma \) vs. ellipticity diagram for dissipational (40\% gas) and dissipationless merger remnants. \( V_{\text{maj}} \) is the maximum rotation speed measured in a slit along the major axis, \( \sigma \) is the velocity dispersion averaged within half of an half-mass radius, and the ellipticity is measured at the half-mass isophote. Further details can be found in § 2.2. The solid line in both plots is that expected for an oblate isotropic rotator (Binney 1978).

Overplotted are data from observed ellipticals from Davies et al. (1983), Bender (1988), Bender & Nieto (1990), and de Zeeuw et al. (2002).

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http://www.journals.uchicago.edu/action/showFullPopup?doi=10.1086/507474&id=e18
THE FUNDAMENTAL SCALING RELATIONS OF ELLIPTICAL GALAXIES

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Received 2005 November 1; accepted 2005 December 6

ABSTRACT

We examine the fundamental scaling relations of elliptical galaxies formed through mergers. Using hundreds of simulations to judge the impact of progenitor galaxy properties on the properties of merger remnants, we find that gas dissipation provides an important contribution to tilt in the fundamental plane (FP) relation. Dissipationless mergers of disks produce remnants that occupy a plane similar to that delineated by the virial relation. As the gas content of progenitor disk galaxies is increased, the tilt of the resulting FP relation increases and the slope of the $R_e - M_e$ relation steepens. For gas fractions $f_{\text{gas}} > 30\%$, the simulated FP scalings ($R_e \propto \sigma^{1.53} L^{0.79}$) approach those observed in the $K$ band ($R_e \propto \sigma^{1.53} L^{0.79}$). The dissipationless merging of spheroidal galaxies and the remerging of disk galaxy remnants roughly maintain the tilt of the FP occupied by the progenitor ellipticals. Dry merging of spheroidal systems at redshifts $z < 1$ is then expected to maintain the stellar-mass FP relations imprinted by gas-rich merging during the epoch of rapid spheroid and supermassive black hole growth at redshifts $z \approx 1-3$. We estimate that $\approx 40\%-100\%$ of the FP tilt induced by structural properties, as opposed to stellar population effects, owes to trends in the central total-to-stellar mass ratio $M_\text{total}/M_*$ produced by dissipation. Gas cooling allows for an increase in central stellar phase-space density relative to dissipationless mergers, thereby decreasing the central $M_\text{total}/M_*$. Lower mass systems obtain greater phase-space densities than higher mass systems, producing a galaxy mass-dependent central $M_\text{total}/M_*$ and a corresponding tilt in the FP. We account for these trends in the importance of dissipation with galaxy mass in terms of the inefficient cooling of collisionally heated gas in massive halos and dynamically varying gas consumption timescales in smaller systems.

Subject heading: galaxies: evolution — galaxies: formation

1. INTRODUCTION

Elliptical galaxies represent a fascinating combination of complexity and regularity. A leading theory for the origin of early-type galaxies is based on mergers of disk galaxies (Toomre & Toomre 1972; Toomre 1977) and likely involves gas dissipation, star formation, and supermassive black hole feedback (Barnes 1992; Barnes & Hernquist 1992, 1996; Mihos & Hernquist 1994, 1996; Di Matteo et al. 2005) in addition to stellar dynamics. Despite their complex origins, early-type galaxies obey a regular set of scaling relations that connect their photometric and kinematic properties, most notably the relation between effective radius $R_e$, central stellar velocity dispersion $\sigma$, and average central surface brightness $I_e$ known as the fundamental plane (FP; Dressler et al. 1987; Djorgovski & Davis 1987)

$$R_e \propto \sigma^{\alpha} I_e^{-\beta}.$$  

The virial theorem can be used to calculate this relation for homologous systems, which gives $\alpha = 2$, $\beta = 1$ (e.g., Faber et al. 1987, hereafter the “virial scaling”).

While the observational determination of the FP was originally motivated as a precise distance indicator to improve on the previously known luminosity-velocity dispersion ($L-\sigma$) relation (Faber & Jackson 1976), the importance of the FP scalings and its correspondingly small scatter for theories of elliptical galaxy formation was also realized. The first observationally determined FP scalings ($\alpha \approx 1.3-1.4$, $\beta \approx 0.8-0.9$, at optical wavelengths; Dressler et al. 1987; Djorgovski & Davis 1987) differed from the virial scaling, indicating a “tilt” relative to the expectation for homologous systems. The FP tilt implied that the mass-to-light ratio $M/L$ likely varies as a function of galaxy mass or luminosity as

$$\frac{M}{L} \propto L^\gamma,$$  

within the range $\gamma \approx 1 - 1/3$. Faber et al. (1987) noted that deviations from the FP can be induced by $M/L$ variance owing to e.g., metallicity or age trends in stellar populations, dynamical or structural properties, and the relative distribution of dark and baryonic matter. In principle, each of these effects may also introduce a systematic tilt into the observed FP if they vary as a function of elliptical galaxy mass.

The purpose of the current paper is to gauge the importance of various contributions to the tilt in the observed FP in the context of the scenario where elliptical galaxies form from mergers. Using hundreds of simulated galaxy mergers that include the physics of gas cooling, star formation, supernova feedback, and black hole accretion and feedback, we determine that gas dissipation may significantly contribute to the tilt of the observed FP, in addition to tilt induced by $M/L$ trends from stellar populations. We propose that elliptical galaxies initially form in gas-rich mergers from disk galaxy progenitors whose gas fractions exceed $f_{\text{gas}} \sim 30\%$, and show that these remnants display substantial FP tilt.

We connect the origin of this tilt to the central stellar phase-space density of the remnants. In small mass systems where dissipation is most important, the stellar phase-space density of
dark matter halos, star formation and supernova feedback. Shown are remnants produced by mergers appropriate for redshifts $z = 0$ (black circles), $z = 2$ (red diamonds), $z = 3$ (blue triangles), and $z = 6$ (green squares) with nearly radial, parabolic orbits. The dissipational merging of pure disk models produces an FP nearly parallel to the observed infrared FP (Pahre et al. 1998b) and is almost independent of the redshift scalings of the progenitor systems. For comparison, the best least-squares fit to the FP delineated by the remnants is plotted (solid line). Also shown is the mean deviation induced by line-of-sight variations in projected quantities for a given remnant (detached error bars).

4.3. Full-Model Disk Simulations

Introducing the effects of black hole feedback through the full-model simulations produces a set of fundamental scaling relations similar to those in dissipational mergers without black holes. The FP produced by the full-model simulations yields nearly the same FP scalings ($\alpha = 1.55$, $\beta = 0.82$) and tilt ($\lambda = 0.79$) as the dissipational simulations (see §4.2), and is similar to the observed near-IR scalings (Pahre et al. 1998b). These simulated remnants exhibit a scatter about their mean FP of $(\Delta \lambda)^{1/2} = 0.062$, comparable to both the observed scatter in the FP at optical wavelengths (e.g., Bernardi et al. 2003a) and that produced by the dissipational simulations. Black hole feedback causes the full-model remnants to be slightly larger than the dissipational model remnants as feedback-driven winds remove gaseous material from the innermost regions of the remnants that would otherwise contribute to the central stellar content. Figure 5 shows the full-model remnants produced by mergers appropriate for various redshifts on nearly radial, parabolic orbits. The resultant FP relation is roughly independent of the redshift scalings of the progenitor systems and the location of remnants within the FP is fairly insensitive to the orientations of the disks (purple pentagons; see Table 2) and orbital configuration (orange hexagons; see Table 2). As these simulations indicate, varying the total angular momentum by changing either the orientation of the disks (spin) or the pericentric passage distance (orbital) does not strongly influence the FP of the remnants. Typically the angular momentum of the orbit only influences the effective radii of the remnants, with the velocity dispersion and surface mass density changing in a compensating fashion to maintain the FP scalings. In addition, varying the concentration of the dark matter halo by a factor of $\sim 2.5$ does little to change the FP scalings (cyan triangles).

The influence of angular momentum on the remnant properties is plainly visible in the $R_e - M_\star$ relation for the full-model simulations (Fig. 6). As is evident in the FP scalings, simulated mergers appropriate for redshifts $z = 0-6$ produce results very similar to the dissipational runs with a comparable $R_e - M_\star$ scaling ($\mu = 0.57$) and slightly larger remnants. However, varying the angular momentum of the merging system through changing the progenitor disk orientations (purple pentagons) and pericentric passage distances for several orientations (orange hexagons) can as much as double the average effective radius of the remnant produced by the same progenitors. The dark matter halo concentration also has a noticeable effect on the galaxy size (cyan triangles). We reiterate that these changes in the effective radius only induce a spread parallel to the FP (see above). Moreover, as is the case for the dissipational simulations without black hole growth, the $R_e - M_\star$ relation for the full-model remnants would only benefit from subsequent remerging or more cosmologically representative orbits by increasing $R_e$.

4.4. Spheroidal Simulations

As demonstrated in §§ 4.1–4.3, the merging of dissipationless disk galaxies produces an FP with almost no tilt relative to the virial plane and a $R_e - M_\star$ relation that is shallower than observed, while gas-rich disk galaxies yield FP relations with substantial tilt and reasonable $R_e - M_\star$ scalings. A natural extension of these calculations is to test whether the subsequent merging of the