Simulating Elliptical Galaxies Throughout the Fundamental Plane

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Introduction

We have developed a simple model to predict the effective radii and velocity dispersions for elliptical galaxies that form through mergers. The model used is a combination of versions presented in Covington et al. (2008, 2011). Using conservation of energy and the virial theorem, we build upon the standard dissipationless predictions (Cole et al. 2000) to include energy lost due to star formation.

By including the model within semi-analytic models (SAMs), we can predict the stellar size-mass and Faber-Jackson relations over a range of redshifts for a large population of elliptical galaxies. Combining this information with the galaxies' ages, metallicities, and luminosities, we show how age and metallicity vary throughout the Fundamental Plane, in direct comparison to Graves et al. (2009).

The Model

$$E_{\mathrm{int,f}} = E_{\mathrm{int,i}} + E_{\mathrm{rad}}$$

$$E_{\mathrm{int,i}} = -C_{\mathrm{int}} G \sum_{j=1}^{2} \frac{\left(M_{\mathrm{stars,j}} + M_{\mathrm{newstars,j}}\right)^2}{R_{\mathrm{stars,j}}}$$

$$E_{\mathrm{int,f}} = \frac{-C_{\mathrm{int}} G M_{\mathrm{stars,f}}^2}{R_{\mathrm{f}}}$$

$$E_{\mathrm{rad}} = -C_{\mathrm{rad}} \sum_{j=1}^{2} K_j f_j i_j (1+i_j)$$

$$R_{\mathrm{stars,f}} = \frac{G C_{\mathrm{int}} \left(M_{\mathrm{stars}} + M_{\mathrm{newstars}}\right)}{E_{\mathrm{int}} + E_{\mathrm{rad}}}$$

$$\sigma^2 = \frac{G C_{\mathrm{sig}} M_{\mathrm{stars,f}}}{R_{\mathrm{f}}(1 - f_{\mathrm{dm,f}})}$$

The energy of the remnant elliptical galaxy ($E_{\mathrm{int,f}}$) is equivalent to the internal energies of the two progenitors ($E_{\mathrm{int,i}}$), plus an additional term accounting for the energy dissipated due to star formation (E_{rad}). Mergers that induce more star formation have higher amounts of dissipation, producing a more compact remnant. The magnitude of star formation is dependent on the mass ratio of the two galaxies as well as their combined gas fraction.

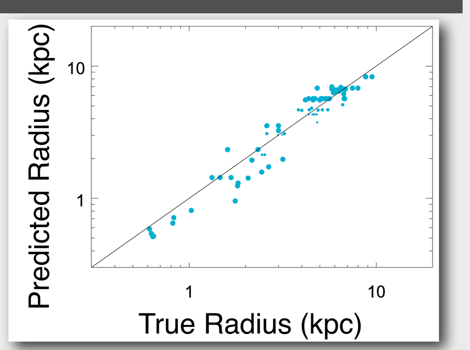
The amount of energy radiated during the merger depends on the total (baryonic plus dark matter) kinetic energy (K_j) and gas fraction (f_j) of the progenitors, as well as the impulse (i_j) between the two galaxies.

The effective radius of the remnant is determining by equating the first and the third equations and solving for the radius.

The velocity dispersion of the remnant is determined by modifying the virial theorem to incorporate the fraction of dark matter within one effective radius ($f_{\mathrm{dm,f}}$) in the remnant.

Calibration with GADGET

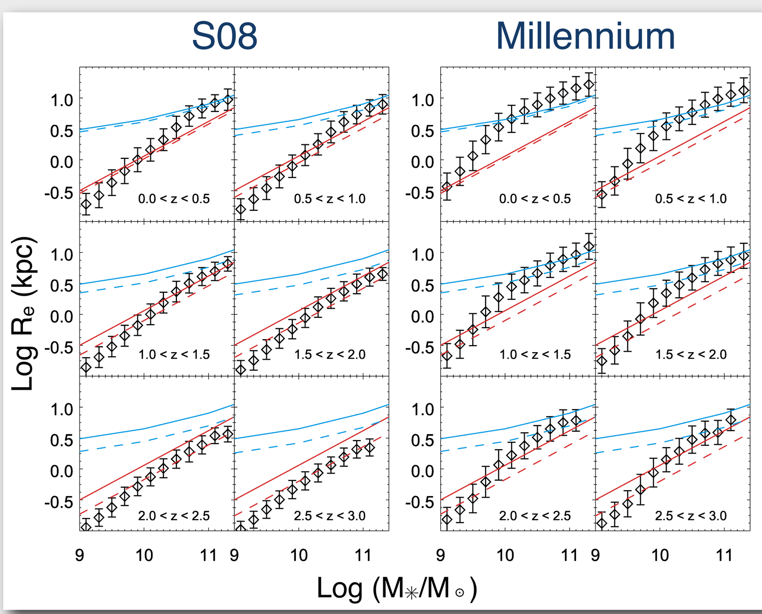
The model was calibrated against a suite of major mergers of two disk-dominated galaxies using the GADGET2 N-Body/SPH code (Cox et al. 2004. 2006, 2008). The scatter in radius was minimized by setting the tunable parameters C_{rad} and C_{int} to 0.5 and 1.0, respectively. With these parameters, the predictions of the effective radius have a χ^2 value of 0.38.



Evolution of the Size-Mass Relation

Using these parameters, the model was applied to two semi-analytic models (Somerville et al. 2008, Croton et al. 2006, termed S08 and Millennium respectively) through post-processing . For each SAM, we have predicted the effective radius and velocity dispersion for all major mergers between disk-dominated galaxies.

The plots at right show the predicted size-mass relations for elliptical galaxies as a function of their formation redshifts. While both SAMs produce a rotation from the observed size-mass relation for spiral galaxies, the S08 SAM produces a better match to observations, partly because the S08 progenitors have more accurate, smaller radii.



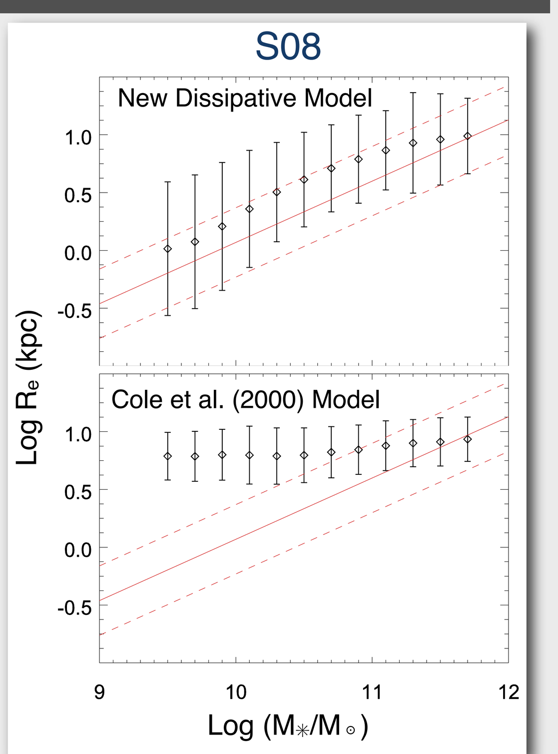
Late-Types — Observed Local Relation (Shen et al. 2003)

Early-Types - - - Observed Relation at Midpoint of Redshift Bin (Trujillo et al. 2006)

Integration within SAMs

To accurately predict the properties of elliptical galaxies at all redshifts, we must expand the merger model to include minor mergers, as well as spiral-elliptical and elliptical-elliptical mergers. This has been done by recalibrating the model presented above to a wider suite of GADGET simulations (Johansson et al. 2009), which includes mergers of varying mass ratios and morphologies. This re-calibrated model has been implemented self-consistently within the S08 SAM.

Preliminary results suggest that the constant C_{rad}, which regulates the amount of energy dissipated due to star formation, decreases for minor mergers between disk-dominated galaxies, and is nearly zero for mergers in which one or both of the galaxies is bulge-dominated. Although the model is still being tuned, the redshift zero size-mass relation is consistent with observations, in contrast to the predictions using the dissipationless Cole et al. (2000) formulae.



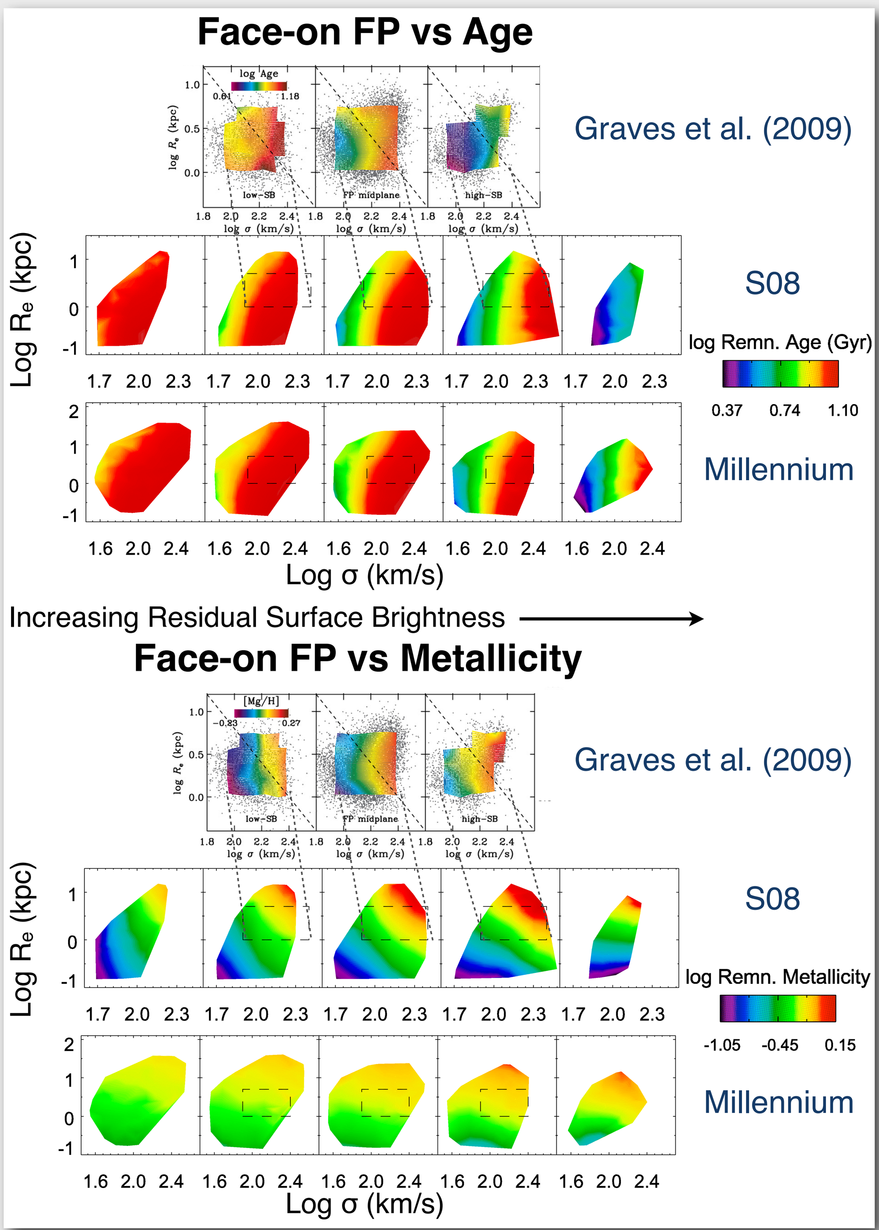
Observed Local Relation (Shankar et al. 2010)

Variation of Age and Metallicity Throughout the Fundamental Plane

Having calculated the effective radii and velocity dispersions for our population of elliptical galaxies, we use the luminosities of the galaxies, calculated within the SAMs, to form a Fundamental Plane (FP) relation between radius, velocity dispersion and surface brightness. To examine galaxies *through* the FP, we separate galaxies into five bins according to their residual surface brightness. Galaxies that lie 'below' the FP have surface brightnesses that are lower than the mean FP relation would predict given their radii and velocity dispersions; galaxies that lie 'above' the FP have relatively higher surface brightnesses. Within each of the five FP bins, we have formed contours relating the face-on FP (radius and velocity dispersion) to the light-weighted ages and metallicities of the galaxies at redshift zero. As the SAMs do not include Type Ia supernovae, our metallicities most closely approximate [Mg/H].

The following plots were made considering all major mergers of disk-dominated galaxies to produce an elliptical remnant that persists until redshift zero, with no subsequent merger activity or star formation. In future work, we will use the full implementation of the model within SAMs to take subsequent evolution into account. Previous SPH simulations (Naab et al. 2009) have shown that subsequent minor mergers between massive ellipticals and smaller spiral galaxies can produce ellipticals with radii that are both larger and more disperse, while leaving the velocity dispersion relatively unchanged. This suggests that when the full model is considered, we will see a stronger trend with velocity dispersion and a weaker trend with radius.

Comparison with Observations



Graves et al. (2009) found that age and metallicity were both strongly dependent on velocity dispersion and weakly dependent on radius. At a fixed radius, galaxies with lower velocity dispersions tend to be younger and more metal-rich.

We find similar trends in age; in addition, galaxies that are younger tend to lie above the FP, in accordance with observations.

In contrast to Graves et al. (2009), we find that metallicity is more strongly dependent on radius than on velocity dispersion. In both cases, the correlations for the remnant elliptical galaxies are rotated approximately 90° from the corresponding relations in the progenitor spiral galaxies, when circular velocity is used instead of velocity dispersion.

Conclusions

We have created a model to predict the effective radii and velocity dispersions of elliptical galaxies that form through major and minor mergers. By including dissipation due to star formation, we are able to produce ellipticals with size-mass relation that is close to observations. In future work, this model will be implemented self-consistently within semi-analytic models, allowing us to predict the evolution of the size-mass relation as a function of redshift.

The major merger model is insufficient to reproduce the observed trends in metallicity throughout the FP, although it is more successful in reproducing the trends in age. This discrepancy stems, in part, from the fact that for spiral galaxies in both SAMs, age is more strongly dependent on circular velocity while metallicity is more strongly dependent on radius. As a result of the major merger, galaxies with higher circular velocities at a given radius tend to contract more than those with lower circular velocities, while there is a high degree of correlation between the progenitors' circular velocities and the remnants' velocity dispersions. The end result is an effective rotation of the correlations before and after the merger: strong correlations in radius before the merger result in strong trends in velocity dispersion after, and strong correlations in characteristic velocity before the merger lead to strong dependences on radius in the remnant.

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