Modelling the Formation of Individual Galaxies:
A Morphology Problem for CDM?

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Abstract. We use a semi-analytic model of halo formation to study the dynamical history of giant field galaxies like the Milky Way. We find that in a concordance LCDM cosmology, most isolated disk galaxies have remained undisturbed for 8–10 Gyr, such that the age of the Milky Way’s thin disk is unremarkable. Many systems also have older disk components which have been thickened by minor mergers, consistent with recent observations of nearby field galaxies. We do have a considerable problem, however, reproducing the morphological mix of nearby galaxies. In our fiducial model, most systems have disk-to-bulge mass ratios of order 1, and look like S0s rather than spirals. This result depends mainly on merger statistics, and is unchanged for most reasonable choices of our model parameters. We discuss two possible solutions to this morphology problem in LCDM.

Keywords: galaxies: evolution, galaxies: structure, cosmology: dark matter

1. Introduction

Recent numerical and semi-analytic models of galaxy formation have made great progress in describing the average properties of populations of galaxies. Given the complexity of these models, however, it is still not clear whether they are based on a complete and definitive picture of galaxy formation. Here we report on preliminary results from a project to test some basic components of galaxy formation models, using galaxy morphology.

We have used the semi-analytic model of Taylor ((2001), see also Taylor & Babul (2001)) to produce individual histories of mass assembly and dynamical evolution for a representative set of CDM galaxy halos. By combining this dynamical framework with a simple prescription for galaxy formation, we can simulate the growth of individual galaxies at negligible computational expense. The systems considered in this work are a set of isolated field galaxies like the Milky Way, in a concordance Ω = 0.3, Λ = 0.7 LCDM cosmology.

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2. Disk Ages

**Thick Disks:** We assume that a collision with a large satellite (half the mass of the disk or more) will disrupt the disk forming at the centre of the main halo. A cumulative distribution of the resulting disk ages is shown in the left-hand panel of Fig. 1.

**Thin Disks:** Minor collisions may heat the thin disk, transforming it into a thick disk. In the right-hand panel of Fig. 1 we show the distribution of thin disk age limits calculated in this way. We find that many systems have thin and thick disk components like those observed in nearby galaxies (Dalcanton & Bernstein, 2002).

**Progressive Disk Heating:** We can also estimate the progressive heating of stars as a function of age. In Fig. 2 we compare the results of individual semi-analytic realisations with the observed age-dispersion relation for the Milky Way, from Quillen & Garnett (2001).

![Figure 1](image1.png)

*Figure 1.* (Left) The cumulative age and redshift distributions of the last major merger, which marks the onset of the formation of the present thick disk. (Right) Same as left panel, but for minor mergers, which set the age of the thin disk.

![Figure 2](image2.png)

*Figure 2.* The predicted increase in velocity dispersion from indirect heating (solid lines), compared with the observed age-dispersion relation (points, from Quillen & Garnett (2001)), and smooth $t^{1/2}$ relations (dashed lines), for three different systems.
3. A Morphology Problem?

Given merger histories for our halos, we add a simple toy model of galaxy formation to predict the growth of the main components of the central galaxy. Hot gas in the halo cools on the infall timescale and is added to the disk, disk material is partially transferred to the spheroid in disruption events, and disrupted satellites are also added to the spheroid (Fig. 3). This model is not designed to provide a detailed account of star formation within each system, but rather to place gross constraints on when the components of field galaxies could have formed.

Exercising the histories of these systems, we notice a trend: massive disks form early and are often disrupted and converted into bulges, producing bulge-dominated morphologies at the present day. While the conversion from mass ratios to galaxy morphologies is problematic, we can indicate the effect schematically by plotting the two components in each system, scaled by their mass (Fig. 4).

![Figure 3](taylor.tex; 19/03/2022; 23:46; p.3)

*Figure 3.* (Left) The growth of the main components in a single system, showing the effects of cooling and disk disruption. (Right) The same for a large set of systems.

![Figure 4](taylor.tex; 19/03/2022; 23:46; p.3)

*Figure 4.* Schematic morphologies for some of our fiducial systems. The spheroids and disks are scaled by the mass of the components in each system, and the disk-to-bulge mass ratio is indicated.
4. Possible Solutions

**Inefficient Starbursts?** In our fiducial model, we assumed that 50% of the disk mass is transferred to the spheroid in the average disruption event, as old disk stars are scattered out of the plane and new stars form in an extended starburst. If high-redshift disks are gaseous and starbursts are inefficient, this conversion rate may be lower and the average disk-to-bulge ratio can increase, as shown in Fig. 5.

**Gas Preheating?** Another possibility is that disk formation is delayed, possibly by some extra source of heat or entropy in the halo gas at early times. If we prevent all cooling prior to $z = 1.5$, we get a better mix of morphologies (Fig. 5, right panel), but this solution may conflict with observations of large disks at high redshift.

![Figure 5. (Left) Schematic morphologies for systems assuming disruptions require a 1:1 collision with a satellite, and transfer only 25% of the disk mass to the spheroid. (Right) Schematic morphologies for systems where cooling is delayed until $z = 1.5$.](image)

5. Conclusion

Examining the dynamical history of galaxy halos in a LCDM cosmology, we find that while the centres of most halos have remained undisturbed for many Gyr, the existence of old, thin and massive components in the disks of galaxies like the Milky Way is still a problem for LCDM, as such systems form early and lose most of their mass through successive disruptive encounters at early times. Thus, unless disks are exceptionally robust, there must be some mechanism which delays cooling and star formation in massive halos at early times. The ‘preheating’ mechanism which appears to produce an entropy floor in cluster gas (Babul et al., 2002) may be one possible candidate.

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