

# EIGHT BILLION YEARS OF DISK GALAXY EVOLUTION

*No galaxy is an island*

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**Abstract** We present a brief discussion of the evolution of disk galaxy stellar masses, sizes, rotation velocities, and star formation rates over the last eight billion years. Recent observations have failed to detect significant evolution in the stellar mass Tully-Fisher relation, stellar mass–size relation, and the stellar mass function of disk galaxies. Yet, most  $z < 1$  star formation is in disks, and this star formation would be expected to drive a rapid growth of the total stellar mass (and therefore mass function) of disks in the last eight billion years. Such a build-up is not seen; instead, a rapid build-up in the total stellar mass in non-star-forming spheroid-dominated galaxies is observed. Large numbers of disk-dominated galaxies are systematically shutting off their star formation and building up a spheroid (or losing a disk) in the epoch  $0 < z < 1$ .

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The evolution of disk galaxy scaling relations — e.g., the luminosity–line-width (Tully-Fisher) relation, or the luminosity–size or stellar mass–size relations — give insight into the evolution of the masses, stellar populations and angular momentum contents of galaxy disks. Luminosity and stellar mass functions give yet deeper insight, as they show how galaxies populate these scaling relations. Here, we present a very brief overview of some recent insights into the evolution of disk galaxy scaling relations, their stellar mass function, and to explore the interplay between star formation and the growth of stellar mass. We will consider only  $z < 1$ , or the last eight billion years or so, given a concordance cosmology ( $\Omega_{m,0} = 0.3$ ,  $\Omega_{\Lambda,0} = 0.7$ , and  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ).

## 1. (Non)-evolution of disk galaxy scaling relations

The evolution of disk galaxy scaling relations has proven difficult to robustly determine, and some issues remain contentious. In some cases (the Tully-Fisher relation: Vogt et al. 1996 vs. e.g., Boehm et al. 2004) it is not clear where the source of the discrepancies lie. In other cases (the luminosity/stellar mass-size relations: e.g., Ravindranath et al. 2004 vs. Barden et al. 2005) the source of the discrepant interpretations has been resolved (see the discussion in Barden et al. 2005).

Barden et al. (2005) present an analysis of the evolution of the disk galaxy luminosity-size, and stellar mass-size relation over the epoch  $0 < z < 1$  from the HST/GEMS (Galaxy Evolution from Morphology and SEDs; Rix et al. 2004) survey of the Extended Chandra Deep Field South. They chart the evolution of the distribution of disk sizes from  $z = 0$  (using the SDSS) to gradually higher and higher redshift, carefully quantifying the effects of surface brightness dimming and incompleteness. At  $z > 1.1$ , the surface brightness limit of GEMS starts to significantly eat into the disk galaxy population, therefore they limited their study to  $z < 1.1$ . Using this sample of galaxies with well-understood and modest completeness corrections, they conclude that:

- there has been significant evolution in the luminosity-size relation, such that galaxies at  $z = 1$  have roughly  $1.5 \text{ mag arcsec}^{-2}$  brighter rest-frame  $B$ -band surface brightnesses than galaxies of equivalent luminosity today; and
- that most of this evolution is attributable to the fading and reddening of stellar populations as they age from  $z = 1$  to the present day, i.e., there is no detectable evolution in the stellar mass-size relation for galaxies with  $M_* > 10^{10} M_\odot$ .

The evolution of the Tully-Fisher relation remains a contentious issue. Nonetheless, important progress is still being made. Novel contributions were made recently by Conselice et al. (2005) and Flores et al. (2006), who presented studies of the  $z < 1$  evolution of the near-IR and stellar mass Tully-Fisher relations. Their analyses ruled out substantial evolution in the stellar mass Tully-Fisher relation<sup>1</sup>.

Also recently, a number of groups have studied the evolution of the stellar mass function of galaxies split either by morphological type or color. These

<sup>1</sup>Conselice et al. then use this as an argument that the dark matter content and baryonic content of disks grow in lockstep, arguing that the stars were a good probe of baryonic mass and the rotation velocity was a good probe of dark mass. Yet, it is important to note that if the bulk of massive disks are maximum-disk (i.e., their baryonic content dominates their rotation velocity; e.g., Kassin et al. 2006, Kassin et al. this volume) then one also expects no evolution in the stellar mass Tully-Fisher relation.

cuts are, at a very general level, largely equivalent — most red galaxies are morphologically early-type and the bulk of blue galaxies are morphologically late-type out to  $z = 0.7$  at least (Strateva et al. 2001; Bell et al. 2004). A general conclusion is that the stellar mass function of blue/disk galaxies does not evolve significantly since  $z = 1$  (see Brinchmann & Ellis 2000 for first indications of this result; Bundy et al. 2006; Borch et al. 2006)<sup>2</sup>.

It would appear that none of the scaling relations defining disk galaxy structure or dynamics, or indeed the space density of disk galaxies at a given mass, significantly change in the last eight billion years. *It is as if the disk galaxy population resolved to do nothing for the last eight billion years except age.*

Yet, there is one observational constraint that has not yet been brought to bear on the problem, which seems to give interesting and incisive insight: the evolution of disk galaxy star formation rates.

## 2. Eight billion years of star formation in disks

With the advent of Spitzer, it has been possible to explore the star formation rates of galaxies at  $z < 1$  with unprecedented accuracy: fully 50% of the  $z = 1$  cosmic SFR has been resolved into individual galaxies with deep  $24\mu\text{m}$  surveys (Le Flocc’h et al. 2005; Zheng et al. 2006). One key result is that the bulk of  $z < 1$  star formation is in disk galaxies: *the order-of-magnitude decline in cosmic SFR is the result of processes which are shaping the evolution of disk galaxies* (Bell et al. 2005; Melbourne et al. 2005; Wolf et al. 2005).

We explore this issue further in Fig. 1. Here, we show the contribution of different types of galaxy to the cosmic SFR and stellar mass budget at  $z < 1$ : such an analysis requires the assumption of a universally-applicable stellar IMF, and we adopt the parameterization of Chabrier (2003) in what follows. Full circles show the total SFR/stellar mass. Open diamonds show the estimated contribution from early-type galaxies. These were selected to be on the red sequence and have concentrated light profiles, with Sersic indices  $n > 2.5$  derived from HST/ACS F850LP imaging data from GEMS. This selection is analogous to that used by McIntosh et al. (2005) for their study of the early-type galaxy stellar mass–size relation. Asterisks show the contribution all other galaxies, dominated by  $n < 2.5$  galaxies (i.e., less concentrated, typically disk-dominated galaxies) with a small contribution from blue galaxies with  $n > 2.5$  (which are often blue disks with significant bulges, or ongoing galaxy mergers). Other ways of splitting the sample — e.g., a pure  $n = 2.5$  split, a pure

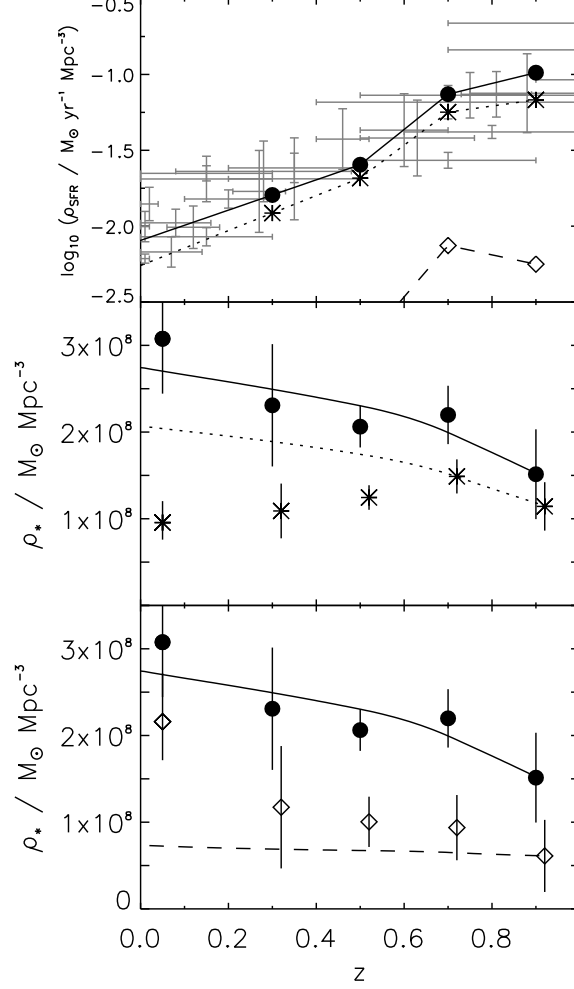
<sup>2</sup>The oft-cited  $\sim 1.5$  magnitude fading of the characteristic luminosity  $L^*$  of the disk galaxy population from  $z = 1$  to the present is more-or-less accounted for by the expected fading and reddening of the ageing stellar populations in blue star-forming disks: thus, the characteristic stellar mass of disks does not appear to evolve a large amount during the last 8 billion years (Lilly et al. 1995; Willmer et al. 2006; Borch et al. 2006; Blanton 2006)

blue/red split, or splits by visual morphology — produce qualitatively similar results to those shown in Fig. 1. The total stellar mass budget is derived from three COMBO-17 photometric redshift survey fields (see Borch et al. 2006); the type-split stellar mass and all SFR budgets used in the argument below were derived from only one field, the extended Chandra Deep Field South for which both HST/ACS data and Spitzer data were available. Uncertainties from cosmic variance have been estimated by exploring field-to-field variation in stellar mass budget of the red and blue galaxy populations (from COMBO-17). The  $z = 0$  point is taken from the SDSS/2MASS (Bell et al. 2003).

In the upper panel of Fig. 1 we show the evolution of the cosmic star formation rate for all galaxies derived from Spitzer  $24\mu\text{m}$  observations (solid circles; Le Floch et al. 2005; Bell et al. in prep.; and grey error bars show the compilation from Hopkins 2004). The asterisks show the evolution of the integrated SFR density in blue/disk-dominated galaxies; the diamonds the contribution from red, early-type galaxies. It is clear that the bulk of star formation is in blue and disk galaxies at all  $z < 1$ .

What do these SFRs predict for the build-up of stellar mass in disks? This is explored in the lower panels of Fig. 1, where we compare the evolution of the integrated stellar mass density with the integral of the star formation rate of different galaxy populations. The evolution of the integrated stellar mass density in all galaxies (solid circles), blue and disk galaxies (asterisks) and red spheroid-dominated galaxies (diamonds) is shown. The lines show the integral of the cosmic SFR: clearly, the evolution of the total cosmic SFR (solid line) is compatible with the observed build-up in cosmic stellar mass density from  $z = 1$  to the present day, with some 40% of stars being formed in this epoch.

Disk galaxies contain the bulk of the star formation. Thus if one assumes that the disk galaxy population is a closed box (i.e., all stars ever formed in disks stay there) then one can predict the growth in the total disk stellar mass density. This result is shown by the dotted line. It is difficult to argue that this mismatch is some kind of catastrophic failure of the stellar mass/SFR estimation methodology: completely standard calibrations were used, and the integral of the cosmic SFR indeed reproduces well the build-up of stellar mass at  $z < 1$ . Instead, it is clear that *the disk galaxy population is not a closed box*. The key to understanding this issue lies in exploring the stellar mass growth in spheroid-dominated galaxies: the total stellar mass in spheroids increases significantly from  $z = 1$  to the present day, while almost no star formation happens in the spheroid-dominated galaxy population. **Large numbers of disk-dominated galaxies are systematically shutting off their star formation and building up a spheroid (or losing a disk)** in the epoch  $0 < z < 1$ . The physical processes that are responsible for these transformations are as yet unclear, and might include bar-induced instabilities, merging with satellites or companions, or suppression of star formation by ram-pressure stripping or galactic winds.



*Figure 1.* The cosmic evolution of star formation rate and stellar mass (filled circles and solid lines), split into contributions from the red, morphologically early-type galaxies (diamonds and dashed lines) and all other galaxies (asterisks and dotted lines; dominated by disk galaxies). In the uppermost panel, determinations of cosmic SFR are shown also in grey, adopted from Hopkins (2004). In the lower panels, the data points show the observed evolution of stellar mass as a function of redshift. The solid line shows the predicted build-up of stellar mass, assuming the star formation history shown by the solid line in the upper panel (assuming for gas recycling); it is clear that the integral of the cosmic star formation history predicts the cosmic evolution of stellar mass at  $z < 1$  reasonably accurately. The dotted line shows the predicted evolution of total stellar mass assuming that all stars that form in blue/disk galaxies remain in blue/disk galaxies (i.e., if the blue cloud evolves like a closed box). The dashed line shows the corresponding evolution for early-type galaxies.

### 3. Discussion

This has important implications for how one interprets the non-evolution of disk galaxy scaling relations. Whereas one could have, without the measurement of the disk galaxy SFRs, postulated that disks were a non- or slowly-evolving population, the evolution of such (expected) rapid star formation-driven build-up in mass makes this interpretation meaningless. Instead, as low-mass disk galaxies are growing in mass (as they must, to replace the disks sacrificed for the ever-growing spheroid-dominated galaxy population), they must be growing also in rotation velocity (to preserve the non-evolving Tully-Fisher relation) and size (to preserve the non-evolving mass–size relation) — at least in an average sense. Furthermore, in this picture, the non-evolution of the stellar mass function of disks is a vital constraint: any mechanism which is transforming disks into spheroids must ‘take’ disks from the stellar mass functions at such a rate that they can be approximately replaced by star formation-related growth of lower-mass disks.

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