Modeling the Evolution of Compact Star-Forming Galaxies

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• Barro et al. (2012) propose a ‘red sequence fast track:’

• ~20% of high-redshift diffuse SFG become compact SFG. These galaxies quench rapidly, followed by a slower growth in size.

• Transition from diffuse to compact triggered by gas-rich processes—major mergers, or dynamical instabilities.

• How well does the SAM recreate this process?
Based off the Somerville et al. (2008, 2012) SAM. Major improvements include:

- Running on the halo merger tree provided by the state-of-the-art Bolshoi simulation, with a WMAP 7 cosmology
- Preservation of disks in gas-rich major mergers (Hopkins et al. 2009)
- Formation of (pseudo)bulges through disk instabilities
- **Full treatment of the growth of elliptical galaxies through major and minor mergers, including dissipative losses due to star formation**
Observations and high-resolution simulations have shown that major mergers of gas-rich spirals induce massive amounts of star formation, typically consuming most of the gas from the progenitor galaxies (Dekel & Cox 2006, Robertson et al. 2006, Wuyts et al. 2010).

- Star formation → energy lost due to dissipation

Covington et al. (2008, 2011): including dissipation naturally reduces the sizes of elliptical galaxies, accounting for the smaller and steeper size-mass relation.

Parameters calibrated to results of GADGET (Cox et al. 2006, Johansson et al. 2009) binary merger simulations. Relative importance of dissipation and internal energy characterized by $C_{\text{dissip}}/C_{\text{int}}$.

- Major disk-disk mergers: $C_{\text{dissip}}/C_{\text{int}} = 3.1$
- Minor disk-disk mergers: $C_{\text{dissip}}/C_{\text{int}} = 1.1$
- All other mergers: $C_{\text{dissip}} = 0.0$

Model velocity dispersion using the virial theorem, including a contribution from dark matter within $1 \ R_e$. 
Gas-poor ‘dry’ mergers increase the radii of the remnants.

Gas-rich ‘wet’ mergers produce remnants with similar or smaller radii as their progenitors.

Gradient in gas fraction with stellar mass can introduce a tilt in the FP and account for the steepening of the size-mass relation from disks to ellipticals.

*Treat disk instabilities as mergers.*
• Compared to the progenitors, remnants are:
  - More compact
  - Steeper size-mass relation
  - Greater evolution with redshift
  - Smaller dispersion in size-mass relation

• Subsequent minor mergers increase the effective radius and the scatter in radius while leaving the velocity dispersion relatively unchanged (Naab et. al 2009, Oser et al. 2012).
• Select all galaxies with $M_\ast > 10^{10} \, M_\odot$ at the desired redshift

• Define compactness as $\Sigma_\alpha = M_\ast / r_e^\alpha$, $\alpha = 1.5$

• Effective radius is mass-weighted average of disk and bulge half-mass radii

• $\log \text{sSFR} \, [\text{Gyr}^{-1}] = -0.5$ separates quiescent (Q) from star-forming (SF) galaxies

• $\Sigma_\alpha = 10.3$ separates compact (c) from diffuse (d) galaxies
Most compact galaxies are quiescent at low redshifts (‘red nuggets’)

Most compact galaxies are star-forming at high redshifts (‘blue nuggets’)

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Red and Blue Nuggets

Most compact galaxies are quiescent at low redshifts (‘red nuggets’)

Most compact galaxies are star-forming at high redshifts (‘blue nuggets’)

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Log $R_e$ [kpc]

-1.0 to 0.5

Compact

Diffuse

Top: $z=0.75$

Bottom: $z=2.40$

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sSFR [Gyr$^{-1}$]

-3.00, -0.89, 1.22
• 23% of galaxies at z=2.8 are cSFG, compared to ~20% in observations.
• Number density declines with redshift, in agreement with observations.

• Theory and observations are qualitatively similar. However, simulated dSFG have lower sSFR than the observations while simulated low-redshift diffuse galaxies have lower surface densities.
- What happens to diffuse SFG at $z=2.8$?
  - Most are quiescent and diffuse (dQ) below $z \sim 1.7$
  - $\sim 10\%$ become cSFG between $z=2.4$ and $z=1.6$

- What happens to compact SFG at $z=2.4$?
  - Most are quiescent and compact (cQ) below $z \sim 1.7$
  - Increase in fraction of diffuse quiescent (dQ) galaxies below $z=1.4$

Barro et al. (2012)
Gas-rich merger in past Gyr
Gas-poor merger in past Gyr
• How important are major mergers in forming cSFG?

• Of cSFG at z=2.8:
  - 11% have had a major merger in the past Gyr (vs 15% of dSFG)
  - 80% have never had a major merger (vs 74% of dSFG)
  - 44% have had a major or minor merger in the past Gyr (vs 53% of dSFG)
  - 28% have never had a major or minor merger (vs 23% of dSFG)
How important are major mergers in forming cSFG?

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Minor mergers and disk instabilities have a large contribution to the population of cSFGs at high redshift.
SAM Conclusions

- Galaxies move from dSFG to cSFG through gas-rich major and minor mergers, as well as classical disk instabilities. Major mergers may not be the dominant mechanism for creating compact galaxies.

- Diffuse and compact SFG may quench at similar redshifts, $z \sim 1.5-1.7$

- Minor mergers decrease the surface density of cSFG, but most remain compact down to redshift 0

- Caveat: outstanding questions about SAM treatment of disk instabilities