Galaxy Formation Models: From Complex to Simple

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Cosmology

Star Formation

Galaxy Formation

Stellar Evolution

Feedback

Chemical Enrichment

Dark Matter

Black Holes
The Illustris Project: AREPO

~6 billion cells
1 kpc resolution
100 Mpc volume

Includes:
Gravity
Gas (moving mesh)
Star formation
Photoionizing bkgd
Black hole growth
10-species chemistry
Type II SNe feedback
Type Ia SNe feedback
AGB stellar evol
AGN feedback

Stars
Gas density
Temp.
Metallicity
Too many small galaxies, particularly at early times!
Stronger feedback in small galaxies to solve GSMF would make MZR discrepancy worse!
No model matches sSFR(z) from z~0-2
Parameterize the baryonic physics:

- SFR
- cooling
- feedback
- merging
- ...
Benson+14: “highly simplified” SAM, “only” 25 parameters. Full MCMC!

Fits GSMF to $z \sim 1$, but badly fails HIMF.
Modeling a concordant galaxy population: Status

Simulations, despite many advances, still can’t match basic demographics of (M*, Z, SFR), even at z=0 let alone to high-z. Improvements still be “trial and error”. How much farther can we take this?

SAMs now employ MCMC etc, but even using 20+ parameters can’t match all properties. Is the basic framework flawed?

Need a simple, robust parameterization that we can easily match to data and that captures insights from simulation.
Hydro Sims: “Baryon Cycling”

The cycle of inflows, outflows, and re-accretion governs the growth and evolution of galaxies.
Galaxies = Gas Processing Factories

\[ \frac{\eta}{(1 + \eta)} + \dot{M}_{\text{recyc}} \]

\[ \xi \dot{M}_{\text{grav}} \]

\[ \frac{1}{(1 + \eta)} \]

\[ \dot{M}_{\text{grav}} \text{ (from IGM)} \]

\[ \text{SFR} = \frac{(\xi \dot{M}_{\text{grav}} + \dot{M}_{\text{recyc}})}{(1 + \eta)} \]

\[ Z = y \frac{\text{SFR}}{\xi \dot{M}_{\text{grav}}} \]

References:
- Finlator+08
- Bouché+10
- Davé+11,12
- Lilly+13
- Dekel+14
Equilibrium Relations

\[ \text{Inflow} = \text{SFR} + \text{Outflow} + \frac{\text{dReservoir}}{\text{dt}} \]

- \( \text{SFR} = (\zeta \dot{M}_{\text{grav}} + \dot{M}_{\text{recyc}})/(1+\eta) \)
- \( Z = y \frac{\text{SFR}}{\zeta \dot{M}_{\text{grav}}} \)
- \( f_{\text{gas}} = (1 + (t_{\text{dep}} s\text{SFR})^{-1})^{-1} \)

where

\( \dot{M}_{\text{grav}} \sim f_b M_{\text{halo}}^{1.1} (1+z)^{2.25} \) [Dekel+09]
Baryon cycling parameters

- **Ejective feedback**
  \[ \eta = \frac{\text{Outflow}}{\text{SFR}} \]

- **Preventive feedback**
  \[ \zeta (J_{\text{UV}}, \text{AGN}, \ldots) \]

- **Wind recycling time**
  \[ t_{\text{rec}} = \text{time for outflow to return} \]

Each depends on \( M_{\text{halo}}, z, \text{etc.} \)

Mitra+14
Parameterize, Bayesian MCMC

 turno we need 8 parameters (Bayesian evidence analysis shows that removing any more is not preferred):

$$\eta = \left( \frac{M_h}{10\eta_1 + \eta_2 \sqrt{z}} \right)^{\eta_3}$$

\[ \zeta_{\text{quench}} = \text{MIN} \left[ 1, \left( \frac{M_h}{M_q} \right)^{\zeta_1} \right], \quad \frac{M_q}{10^{12} M_\odot} = (0.96 + \zeta_2 z). \]

$$t_{\text{rec}} = \tau_1 \times 10^9 \text{yr} \times (1 + z)^{\tau_2} \left( \frac{M_h}{10^{12}} \right)^{\tau_3}$$

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Observational Constraints

- $M_\star - M_{\text{halo}}$ (equivalent to GSMF, $z=0-2$): Inferred from GSMF($z\sim0-6$) data, consistent with SFR evolution. [Behroozi+13, Moster+13].

- **Mass-Metallicity relation:** Now seen out to $z\sim2$ thanks to Keck/Mosfire. [Steidel+14, Sanders+14]

- **SFR-$M_\star$ ($z=0-2$):** Recent compilation with consistent calibrations from Speagle+14. [also Whitaker+14, Schreiber+14].
Equilibrium Model: MCMC constraints ($\chi^2 \sim 1.6$)

M$_*$-M$_{\text{halo}}$

M$_*$-SFR

M$_*$-Z
Fit only to $M_*-M_h$, SFR-$M_*$, predict $M_*-Z$ ($\chi^2 \sim 2.0$)
Outflows stronger in low-mass galaxies

- $\eta \sim M_h^{-1.2} \sim M_*^{-0.3}$
- Stronger at hi-z
- FIRE (Muratov+15): $\eta \sim M_*^{-0.35}$, amplitude like at $z \sim 2$ but invariant w/z.
- $t_{\text{rec}} \sim M_h^{-0.45} \sim M_*^{-0.2}$
- Opp, RD+08, 10 best-fit hydro sims: $t_{\text{rec}} \sim M_h^{-0.5}$

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Parameter constraints

\[ \eta = \left( \frac{M_h}{10^{10.98 + 0.62\sqrt{z}}} \right)^{-1.16} , \]

\[ t_{\text{rec}} = 0.52 \times 10^9 \text{yr} \times (1 + z)^{-0.32} \left( \frac{M_h}{10^{12}} \right)^{-0.45} \]

\[ \zeta_{\text{quench}} = \text{MIN} \left[ 1, \left( \frac{M_h}{M_q} \right)^{-0.49} \right] , \]

where \( \frac{M_q}{10^{12} M_\odot} = (0.96 + 0.48z) \).
Evolution of scaling relations

Can now fit sSFR(z) at z~2!

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What is it good for?

- Get SFR and Z histories for given $M^*, z$.
- Serve as input into cosmological sims that include feedback.
- Make predictions for evolution to higher $z$.
- Populate N-body with “average” galaxies.
- New framework for understanding galaxy formation.

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What’s left to be done?

LOTS!

Consider *scatter*: Fluctuations in gravitational inflow rate, plus(?) excursions via major mergers.

Include *gas* (HI, H$_2$): Compare/constrain to data

Model *satellites*: Affected by stripping processes.

Examine *environment*: Formation time bias, …

Compare with hydro simulations w/same parameters

Implement into full N-body simulations.
Intuition from the Equilibrium Model

- Stellar and metal growth limited by cooling rate and conversion of gas into stars.
- Ejective and preventive feedback.
- Metal & gas content reflects "evolutionary state".
- Gas supply vs. consumption rate.
- Mergers drive galaxy evolution are subdominant to cold streams for fueling.
- Galaxies & IGM evolve independently are connected by baryon cycling.

Summary

- Despite advances in simulations and semi-analytic models, our physical galaxy formation model remains incomplete.

- The equilibrium model provides a new, simple, and robust approach to phenomenological galaxy formation, based on the simulation-motivated framework of baryon cycling.

- This model is able to fit key data across cosmic time with reasonable baryon cycling parameters, in which:
  - small galaxies eject a larger fraction of accreted gas
  - recycling is more rapid in high-mass galaxies
  - quenches at a mass that evolves modestly upwards with $z$