What regulates star formation?

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M. Murphy (Swinburne), C. Martin (UCSB), T. Contini (Toulouse)
Great Success

Hopkins Beacom 2008

Bouwens et al. 2009
What drives star-formation?

**a)**

*merger scenario* motivated by hierarchical merger merger model:

Hernquist, Springel, di Matteo, Hopkins et al. 2003-2006

**b)**

*rapid inflow scenario*:

Dekel & Birnboim 2003, 2006, Keres et al. 2005,
Teyssier et al.

AMR, Teyssier
What drives star-formation?

c) Gas reservoir sets SFR

Kennicutt 1998
Continuous flow(s)

Primordial fluctuations

Biegel et al. 2008, 2011

H+ → HI → H₂
Continuous flow(s)

Primordial fluctuations

Growth/Accretion

NGC 3184
What is the role of feedback?

Behroozi et al. 2009
Scaling relations

- **KS Relation**
  \[ \Sigma_{\text{SFR}} \sim \Sigma_{\text{gas}}^{1.5} \]

- **SFR-Mass**
  \[ \text{SFR} \sim M^{0.8} \]

- **TF**
  \[ M \sim V^4 \]

See Genzel et al 2010, Daddi 2010
Scaling relations

- **KS Relation**
  \[ \Sigma_{SFR} \sim \Sigma_{\text{gas}}^{1.5} \]

- **SFR-Mass**
  \[ \text{SFR} \sim M_*^{0.8} \]

- **TF**
  \[ M_* \sim V^4 \]

Cresci et al. 2009, also Kassin.
Scaling relations

• KS Relation
  \[ \Sigma_{\text{SFR}} \sim \Sigma_{\text{gas}}^{1.5} \]

• SFR-Mass
  \[ \text{SFR} \sim M^{0.8} \]

• TF
  \[ M \sim V^4 \]
The SFR sequence at z=0.5-1 and z=1.5.

Also, Damen 09, Zheng 07.
The SFR sequence

Karim et al. 2010
(COSMOS $10^5$ galaxies)

Genel 2008, Neistein 2007
McBride/Fakhouri
Evolution is a challenge

Davé 2008

Oliver et al. 2010
Evolution at $z > 4$?

Based on data from:
- Noeske et al. 2007
- Daddi et al. 2007a
- Stark et al. 2009
- This work

Gonzales 2010
Open Questions

• Why is there SFR-Mass?

• Why evolution x20 since z~2?

• Why is there downsizing?

  – Role of gas inflow vs. impact of feedback?
Galaxy Formation: Traditional

- Hydro Simulation
Traditional Approach

White & Frenk 1991

Birnboim & Dekel 2003
Keres et al. 2005; Ocvirk + Teyssier et al.

Cooling Rate
Infall Rate

Metals

$T_{\text{kev}}$

$V_c/\text{km} \cdot \text{s}^{-1}$

$log(T/\mu)$

$\rho/\langle \rho \rangle$

Hot gas
Diffuse Gas
Cold Gas
Galaxy Formation: Approach 3

dM/dt \sim 35 \ M_h^{1.1} \ (1+z)^{2.2}

Genel et al. 08, also Fakhouri, Ma; McBride et al.
Scaling relations: Summary

- KS Relation
  - $\Sigma_{SFR} \sim \Sigma_{gas}^{1.5}$

- SFR-Mass
  - $SFR \sim M_{*}^{0.8}$

- Halo Growth
  - $dM/dt \sim M^{1.1}$

- TF
  - $M_{*} \sim V^4$
Scaling relations: Summary

• KS Relation
  \[ \Sigma_{\text{SFR}} \sim \Sigma_{\text{gas}}^{1.5} \]

• SFR-Mass
  \[ \text{SFR} \sim M_*^{0.8} \]

• Halo Growth
  \[ \frac{dM}{dt} \sim M^{1.1} \]

• Virial relation
  \[ M \sim V^3 \]

• TF
  \[ M_* \sim V^4 \]
Disclaimer
Bathtub model: Solutions

\[ dM_{\text{gas}} = \varepsilon_{\text{in}} \frac{dM}{dt} - \text{SFR} - \text{Outflow} \quad (1) \]

\[ \text{SFR} = \varepsilon_{\text{sfr}} \frac{M_{\text{gas}}}{t_{\text{orb}}} \quad (2) \]

KS \(\Rightarrow\) The bathtub NEVER overflows!! Reach a quasi-steady state.
Quasi-Steady State: Implications

- \( t_{\text{sfr}} \ll t_{\text{acc}} \)

\[ \rightarrow \quad \text{SFR follows net gas inflow rate} \]
Bathtub model

\[ dM_{\text{gas}} = \varepsilon_{\text{in}} \frac{dM}{dt} - \text{SFR} - \text{Outflow} \quad (1) \]

\[ \text{SFR} = \varepsilon_{\text{sfr}} \frac{M_{\text{gas}}}{t_{\text{orb}}} \quad (2) \]
Option 1: Change SF efficiency

SFR sequence

TF relation

Same for SF threshold!
Option 2: Change feedback

Dutton et al. 2009, 2010

==> Good for M-Z relation
Option 2: Change feedback

Dutton et al. 2009, 2010

See also Finlator et al. 2011
Option 3: Change accretion

\[ \dot{M} = \frac{M_{\text{in}}}{M_{\text{in}} - M_{\text{out}}} \]

\[ M_{\text{in}} = \frac{M_{\text{shock}} - M_{\text{min}}}{1 - \varepsilon_{\text{in}}} \]

\[ M_{\text{out}} = M_{\text{shock}} - M_{\text{min}} \]

\[ \varepsilon_{\text{in}} = 0 \Rightarrow \text{No Accretion} \]

\[ \varepsilon_{\text{in}} \text{ high; Stars can form} \]

\[ M_{\text{shock}} \]

\[ M_{\text{min}} \]

Bouché et al. 2010, see also Cattaneo et al. 2010

Neistein, E., Weinmann, S. 2010
Scaling Relations

SFR sequence

TF relation

Without Minimum Mass
Scaling Relations

SFR sequence

TF relation

With Minimum Mass  Bouché et al. 2010
Bouché et al 2010
Scaling relations are isochrones

- Finlator et al. 2011; SPH
- Bouché et al. 2010
Other predictions

- SFR-Mass; TF
- sSFR (z)
- Stellar fractions
- F_gas (M*)
- F_gaz (z)
- SFRD (z)
- Downsizing
Predictions 1: Stellar fraction
Predictions 2: Gas fractions

High accretion $\rightarrow$ high SFR $\rightarrow$ high $f_{\text{gas}}$

Daddi et al. 2010

$M_*/(M_\text{gas} + M_*)$

$\log M_* = 10.3$

$\text{SSFR} = \text{SFR}/M_*$ [Gyr$^{-1}$]

$0 < z < 2.5$

Average trend
Prediction 3: Evolution SFR(z)

Bouché et al. 2010
Open Questions

• Why is there SFR-Mass?

• Why evolution x20 since $z \sim 2$?
  – Role of gas inflow vs. impact of feedback?

• What causes downsizing?
Scaling relations: Summary

• Halo Growth
  \( \frac{dM}{dt} \sim M^{1.1} \)
  (Genel et al. 2008, Neistein et al. 2008)

• KS Relation
  \( \Sigma_{\text{SFR}} \sim \Sigma^{1.4} \)

• SFR-Mass
  \( \text{SFR} \sim M^{0.8} \)

• TF: \( M \sim V^4 \)
Toy Model: One Assumption

- \( \epsilon_{\text{in}} = 0 \): No Accretion
- \( M_{\text{max}} \) and \( M_{\text{min}} \): Mass ranges
- \( z \): Redshift range
- SFR \( [M_\odot/\text{yr}] \): Star Formation Rate
Downsizing

Archeological Downsizing

$1+z_{\text{form}}$ vs. $\log M_*$ [M$_\odot$]

$z=0.0$ accFloor

$\alpha M^{0.3}$ (Noeske07)

SFR [M$_\odot$/yr] vs. Time [yr]
Casey's trick
Evolution at $z>4$?

- **Power law:**
  \[ \tau \sim 200 \text{ Myr} \]

- **Rising Exponential:**
  \[ \tau \sim 400 \text{ Myr}! \]

For a SFR that evolves as $\Psi(t) \sim t^\alpha$ (equation 3) the stellar mass evolves roughly as $M_*(t) \sim \int \Psi(t) \, dt \sim t^{(\alpha+1)}$. 

![Graph showing SFR evolution over redshift and lookback time](image)
Evolution at $z>4$?

Finlator et al. 2011; SPH

Bouché et al. 2010

\[
\begin{align*}
\text{log}(\frac{M_*}{M_\odot}) &= 9.7 \\
9.2 & \\
8.7 & \\
8.2 & \\
\text{redshift} & = 15, 12, 10, 9, 8, 7, 6 \\
\end{align*}
\]

\[
\begin{align*}
\text{log}(\text{SFR}) & = [M_\odot/\text{yr}] \\
\text{log}(\text{SFR} /[\text{SFR}]) & = 0, -1, -2 \\
\tau(z) & = 0.5 \text{Gyr}/(1+z)^{2.2} \\
\tau & = 0.5 \text{Gyr} \\
\end{align*}
\]
Evolution at $z>4$?

Based on data from:
- Noeske et al. 2007
- Daddi et al. 2007a
- Stark et al. 2009
- This work

$\log M_\odot = \begin{cases} 9.5 \\ 10.0 \\ 10.5 \end{cases}$

Stark et al. 2009
Gonzales et al. 2009

Bouché et al. 2010
Problems at $z>4$?

- SFH(t) assumed...
- Emission lines
- Dust

Schaerer et al. 2010
Problems at $z>4$?

- SFH(t) assumed...
- Emission lines
- Dust

- No one
- Not in Gonzalez
  sSFR underestimated
- No near-IR in Yabe
  SSFR overestimated
In Summary: Mass accretion Floor

What is the physical mechanism?

A) Traditional
- UV heating? Only works in halos <10 km/s
- Feedback?
- Re-heating / Mo 2005
- H$_2$ formation / Robertson

B) Cooling / Cantalupo 2009
  + Globular Clusters can reionize universe...

Is there evidence for a mass floor?
Cooling Curve !

Cantalupo 2010

Figure showing cooling curves as a function of temperature and time for different metallicities and velocities.
SINFONI MgII Program for Line Emitters (SIMPLE): 14/21 (70%) detections (WR>2 Å)

SDSSJ2335 EW=3.3  2QZJ2357 EW=1.9  2QZJ0302 EW=2.2  SDSSJ0822 EW=2.70  SDSSJ0427 EW=2.0

SDSSJ0147 EW=4.0  SDSSJ1422 EW=3.2  SDSSJ0943 EW=3.5  

2QZJ0226 EW=4.5  SDSSJ0448 EW=3.2  2QZJ0248 EW=2.5

Bouché et al. 2007
Evidence from MgII Surveys?
Evidence for the accretion floor?
Implications

- Metal rich halos came first...
Would cold flows be ever observed?
Galaxy formation with MUSE

- Giant IFU 1’x1’ (optical)
  - AO enhance
  - Great stability
  - High sensitivity (3e-19 erg/s/cm², 1e-18 cgs/sq”)

PI: Bacon (Lyon)
$F(\text{Ly}a) = 3 \times 10^{-18}$ cgs