Star formation during the first three billion years: the key to understanding galaxy formation

Late-type

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with

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Galactic-scale star formation observation meets theory
Cosmic-scale star formation
average star formation history in the universe
from current observations

“The universe got tenure at z~2” – Hans-Walter Rix

from Behroozi et al. 2012. arxiv/1207.6105
However, upon closer examination...
only massive galaxies tenured by $z \approx 2$; late-type progenitors were still in the postdoc mode at that epoch

star formation histories of galaxies in halos of different final mass (at $z=0$) derived from abundance matching approach

Behroozi et al. arxiv/1207.6105 (cf. also Moster et al., arxiv/1205.5807)

Final stellar mass = integral over star formation history

$$M_* = \int \dot{M}_*(t) dt$$

but SFH itself critically matters in setting galaxy properties, such as morphology

low star formation rates are expected in halos of mass $< \sim 10^{12}$ M$_\odot$ (at $z=0$)
Galaxies forming in small mass halos convert only a small fraction of accreted gas mass into stars -> star formation at high z in such objects should be very inefficient (level of suppression comparable to early type galaxies at z~0)

low star formation rates are expected in halos of mass $<10^{12}$ Msun (at z=0)
Observations indicate that spiral galaxies at low $z$ form $>80\%$ of their stars at $z<2$.

Star formation histories derived from observed evolution of the SFR-$M^*$ relation.


Final ($z=0$) stellar masses of galaxies.
Star formation histories of galaxies in cosmological simulations typically exhibit high star formation rates at high $z$

this is the main reason galaxy formation simulations tend to produce mostly early-type like galaxies with massive spheroids

Most of $L < L^*$ galaxies look like this...

NGC 253

composite R, G, B image
S. Mazlin et al.
Star Shadows Remote Observatory/PROMPT

http://www.starshadows.com/gallery/display.cfm?imgID=319
30 kpc

Stinson et al. 2010
MNRAS 408, 812
arXiv/1004.0675

projected stellar density for 9 different simulated galaxies of different stellar masses

color of stellar particles indicates their age (blue=young; reddish=old)
projected stellar density
In three projections (rows) of four MW-sized simulated galaxies (columns)

the stars in the simulated galaxies are kinematically hot, which is reflected in prominent central spheroidal component and thick disk

Scannapieco et al. 2009 MNRAS 396, 696
re-simulation of the Aquarius MW-sized halos

Scannapieco et al.
2011 MNRAS 417, 154

projected stellar surface density in i-band for 8 simulated galaxies (face-on and edge-on)
Fairly realistic MW-like galaxy produced in the Eris simulation


Spheroidal component is largely built from stars formed at $z>2$

bulge/disk ratio = 0.35

15 kpc

SFR [M$_{\odot}$yr$^{-1}$]

$M_*$ [M$_{\odot}$]

redshift
There is a distinct correlation between amount of early star formation and fraction of stars that end up in the disk formation of “bulgeless” galaxies requires very inefficient star formation at z>2


Expansion factor at which 50% of stars were formed

fraction of stars in disk in simulated galaxy at z=0

smaller disk fraction $f_{(\epsilon>0.8)}$ larger disk fraction

$\alpha_{50\%}$
Star formation at high z may be less efficient because galaxies have lower metallicities (and less dust) and higher interstellar FUV fluxes (smaller fraction of gas is shielded from FUV radiation).

\[ M_\star = \int \dot{M}_\star(t) \, dt \quad \dot{M}_\star = \int \dot{\Sigma}_\star \, dA \]

\[ \dot{\Sigma}_\star = f(\Sigma_{\text{gas}},...) = \frac{\Sigma_{\text{gas}}}{\tau_{\text{sf}}} \]

Kennicutt-Schmidt relation

Can we modulate star formation history simply by modulating gas consumption time scale? (i.e., without modifying \( \Sigma_{\text{gas}} \))
Gas consumption time is large in low-surface density and low-metallicity environments.

\[ \tau_{sf} = \frac{\sum_{gas}}{\sum_{*}} \]

**blue = local galaxies**

Biegel et al. 2008, 2011

**magenta = low metallicity galaxies**

(Wolfe & Chen '06)

(Rafelski et al. '11)

(Bolatto et al. '11)

**red =**

Depletion time

(Just another way of plotting the KS relation)

\[ \tau_{sf,H_2} = \frac{\sum_{H_2}}{\sum_{*}} \]

Bigiel et al. '08, '11

Genzel et al. '10

Schruba et al. '12

\[ \Sigma_{gas} \text{ (M}_\odot \text{ pc}^{-2}) \]

\[ 1 \quad 10 \quad 100 \]

\[ 10^8 \quad 10^9 \quad 10^{10} \]
Environmental dependence of star formation

\[ M_* = \int \dot{M}_*(t) dt \quad \dot{M}_* = \int \dot{\Sigma}_* dA = \int f_{H_2} (\Sigma_{\text{gas}}) \frac{\Sigma_{\text{gas}}}{\tau_{\text{sf},H_2}} dA \]

\[ \dot{\Sigma}_* = \frac{\Sigma_{\text{gas}}}{\tau_{\text{sf}}} = \frac{\Sigma_{H_2}}{\tau_{\text{sf},H_2}} = f_{H_2} (\Sigma_{\text{gas}}) \frac{\Sigma_{\text{gas}}}{\tau_{\text{sf},H_2}} \]

\[ f_{H_2} = f(Z, J_{\text{UV}}, \Sigma_{\text{gas}}, \ldots) \quad \text{e.g., Elmegreen '93, Schaye '01} \]
Dynamical model for formation and destruction of $H_2$
(cf. Robert Feldmann's talk earlier today)

\[
\dot{\rho}_* = \frac{\rho_{H_2}}{\tau_{H_2}} \quad \text{where} \quad \tau_{H_2} = 1 \text{ Gyr} \left( \frac{n_H}{50 \text{ cm}^{-3}} \right)^{-1/2}
\]

volume rendering of HI density

regions of $f_{H_2} > 0.1$

ART simulation, resolution $\sim 50$ pc
inefficiency of gas conversion into stars in low-metallicity, high-redshift small-mass galaxies

→ suppresses star formation in halos of $M_h < 10^{10}$ $M_{\odot}$ at high $z$

Gnedin & Kravtsov

Kuhlen et al. 2011
arXiv/1105.2376

$z=3$
Inefficient star formation by itself will not solve problems such as the baryon concentration problem (baryon distribution is too concentrated towards the center).

**ART code simulations of a MW-sized object with peak resolution of 80 pc (physical) within the disk, molecular hydrogen chemistry and 3d radiative transfer**

Our simulations fail to reproduce the high column density tail of the DLA NHI distribution

even though they include $H_2$ physics, radiative transfer, etc.

The culprit is the dense central concentration of gas in gaseous disks (ubiquitous in simulations with inefficient feedback)

e.g., Hummels & Bryan 2012; Scannapieco et al. 2012

Denis Erkal (U.Chicago)
Need to model the star formation-feedback loop fully and correctly

\[
\dot{M}_* = \int f_{H_2}(\Sigma_{\text{gas}}) \frac{\Sigma_{\text{gas}}}{\tau_{\text{sf}, H_2}} dA
\]

In addition to correctly modelling gas consumption time scale, we need to model structure of gaseous disk ($\Sigma_{\text{gas}}$), which is very likely modified by feedback.

Challenge going forward is to figure out the correct balance of star formation efficiency (should be quite low on average) and seeming requirement that feedback should be efficient.
New subgrid model for stellar feedback which takes into account momentum injection due to radiation pressure and winds during early stages (< 4 Myr) of stellar evolution (Agertz, Kravtsov, Leitner & Gnedin 2012, in prep.)

see Oscar Agertz’s poster for more details:

Stellar feedback and efficiency of star formation

Oscar Agertz,Andrey V. Kravtsov, Samuel N. Leitner, Nickoley G. Gnedin

Abstract

Stellar feedback is thought to play a major role in galaxy formation and evolution by regulating star formation, driving interstellar turbulence and generating galactic-scale outflows. We have developed a new model of stellar feedback that takes into account both energy injection by supernovae and momentum injection from stellar winds and radiation pressure during the first 4 Myr of stellar evolution. We show that early momentum injection makes stellar feedback much more efficient, because it drives dense star-forming gas clouds through powerful supernova and wind energy inputs. Simulations of isolated spiral galaxies indicate that stellar feedback can both suppress and self-regulate the global efficiency of star formation. We compare our results to another widely used model of feedback, in which there is no early stage of feedback, and gas heated by supernova energy injection is not allowed to cool for a certain period of time. Although we find that star formation rate suppression is comparable in these two models, there are significant differences in SFH structure and cosmic star formation histories in cosmological galaxy formation simulations.

The stellar feedback budget

In the figure to the right, we plot the specific radiation and mechanical power from stellar winds and SN driven from a stellar population assuming a 

\[ P_{\text{rad}} = \alpha \times (L_{\text{bol}} + L_{\text{UV}}) \]

\[ P_{\text{mech}} = \beta \times (L_{\text{bol}} + L_{\text{UV}}) \]

\[ P_{\text{mech}} = \gamma \times (L_{\text{bol}} + L_{\text{UV}}) \]

\[ P_{\text{mech}} = \delta \times (L_{\text{bol}} + L_{\text{UV}}) \]

where \( P_{\text{rad}} \) is the infrared radiative flux, \( P_{\text{mech}} \) is the mechanical energy, \( L_{\text{bol}} \) is the bolometric luminosity, \( L_{\text{UV}} \) is the UV luminosity, \( P_{\text{mech}} \) is the mechanical energy, \( P_{\text{mech}} \) is the mechanical energy, and \( P_{\text{mech}} \) is the mechanical energy. These parameters are defined in the figure above.

The effect of radiation pressure may also be significantly enhanced in dense, dusty regions as UV photons absorbed by dust reemitted in infrared, while multiple scattering events may occur in general, the radiation momentum injection rate can be written as:

\[ P_{\text{rad}} = \alpha \times (L_{\text{bol}} + L_{\text{UV}}) \]

\[ P_{\text{mech}} = \beta \times (L_{\text{bol}} + L_{\text{UV}}) \]

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The effect of pre-supernova feedback on a star forming cloud

The global stellar feedback efficiency is found to be self-regulated, being in the range of 0.25–0.5 of the global feedback efficiency.

Preliminary results from cosmological simulations

Star formation histories for a Milky Way galaxy

Without feedback, stars are overproduced throughout the cosmic history, with a peak around z ~ 3. Feedback can lower star formation rates, but even for simulations adopting delayed cooling (too early SNIa feedback) higher feedback is required (blue line) to decrease star formation to more realistic levels.
Importance of early, pre-supernovae stellar feedback

(Agertz et al. ‘12, see also, Murray et al. 2005, 2010; Hopkins et al. 2011a,b,c,d; Stinson et al. 2012, arxiv/1208.0002)

\[
E_{\text{tot}} = E_{\text{SNII}} + E_{\text{SNIa}} + E_{\text{wind}}
\]

\[
p_{\text{tot}} = p_{\text{SNII}} + p_{\text{wind}} + p_{\text{rad}}
\]

these three are comparable and radiation pressure may even dominate in high-density regions of young embedded clusters

\[
\dot{p}_{\text{rad}} = (1 + \tau_{\text{IR}}) \frac{L}{c}, \quad \tau_{\text{IR}} = \kappa_{\text{IR}} \Sigma_{\text{gas}}
\]

Idealized spherical cloud simulation with early momentum injection and subsequent supernova enerhy injection:

NGC 602 (young star cluster in the SMC)
Early momentum injection generally makes stellar feedback much more efficient in disrupting star forming clouds and re-distributing gas within the disk.

(cf. also, Hopkins et al. 2011a,b,c,d; Hummels & Bryan 2011)

temperature maps in simulations of isolated MW-sized disk

<table>
<thead>
<tr>
<th>No feedback</th>
<th>All feedback</th>
<th>All feedback</th>
<th>All feedback</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>40 Myr delayed cooling</td>
<td>fixed $\tau_{IR}=30$</td>
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Agertz et al. 2012 in prep
Efficient feedback tends to self-regulate star formation efficiency (i.e., normalization of the Kennicutt-Schmidt relation) (Agertz et al. '12, in prep; cf. also, Hopkins et al. 2011; Dobbs et al. 2011)

weak feedback:
linear dependence of KS normalization on assumed SF efficiency

strong feedback:
much weaker dependency on assumed SF efficiency

grey points = Bigiel et al. '08
Preliminary results from cosmological simulations indicate that Early stellar feedback can help to significantly reduce star formation at high $z$.

\[ \text{Agertz et al. '12 In prep.} \]
Preliminary results from cosmological simulations indicate that Early stellar feedback can help to significantly reduce star formation at high z

(Stinson et al. ‘12, arxiv/1208.0002 = today)

buildup of stellar mass (relative to total halo mass) in galaxy formation simulations with different feedback prescriptions/parameters
Galaxy morphology is very sensitive to star formation history during the first 3 Gyrs of evolution of the universe (z>~2). Star formation should be highly suppressed to form late type disk galaxies.

- At the same time, stellar feedback should be very efficient to redistribute gas in the forming disks and drive outflows.

- Lots of progress in understanding what was missing in simulations of galaxy formation. The challenge going forward is to figure out details of the star formation-feedback loop.

(in particular how to reconcile inefficiency of star formation required by observations and basic physical considerations AND need for strong and efficient stellar feedback.)
Sensitivity of the Schmidt-Kennicutt relation to varying dust-to-gas ratio

Test models simulated to z=3 but with different fixed dust-to-gas ratios and interstellar UV fluxes show that the main difference is gas metallicity.


observed: Kennicutt 1998 fit
observed: Bigiel et al. 2008 (gray band)

Surface density of star formation rate measured in 500 pc patches