Understanding Galaxy Evolution with Massive Starburst Galaxies

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Galaxy 101: The Andromeda Galaxy

- It is made of stars, gas, & dust
  - Stellar Mass: $1.3 \times 10^{11} \, M_{\odot}$
  - Molecular Gas Mass: $4 \times 10^{8} \, M_{\odot}$
    - Molecular gas is mostly $H_{2}$ but is traced by CO
  - Dust Mass: $8 \times 10^{7} \, M_{\odot}$
    - Dust obscures optical light but glows in infrared

- Its star formation rate (SFR) is $1 \, M_{\odot}$ per year

- It lives in a dark matter halo
  - Halo Mass: $1.2 \times 10^{12} \, M_{\odot}$
    - $>10x$ greater than the visible mass

Key Diagrams:
- Optical $\rightarrow$ Stars
- CO $\rightarrow$ H$_2$ gas
- Infrared $\rightarrow$ Dust
Galaxy 101: Color Bimodality - Galaxies are either blue or red

Hubble’s Galaxy Classification Scheme

Red Ellipticals (old stars)

Blue Spirals (young stars)

Galaxies in the Current Universe
Galaxy 101: Color Bimodality: Galaxies are either blue or red

Red Sequence: *Old Ellipticals*

Blue Cloud: *Young Spirals*

Now

6 Gyr ago

Blanton+2006

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Red Galaxy Formation

- **Early Completion:** Most of the stellar mass in the red sequence is already in place by $z = 1$
- **Rapid Build-Up:** Stellar mass density increased more than 10 times in just 2 billion years ($1 < z < 2$).
Outline

• Galaxies show two main flavors -- blue or red -- in the past 10 Gyrs (or 70% of the universe’s life), and red galaxies formed early and rapidly.

• A model of galaxy formation & evolution:
  ✓ the evolution in global star formation level
  ✗ why galaxies are either blue or red?
  ✗ dusty galaxies with tremendous star formation rates

• Why dusty galaxies are key to understand the divide between the blue and red galaxies?

• Prospects of a physical understanding of galaxy evolution with future observations
Physical Processes in Galaxy Evolution

Star Formation: Converting gas into stars

Feedback: Ejecting gas

Gas accretion
The “Bathtub” Model

Gas reservoir in MS SFGs

Gas accretion from halo

Gas return from:
- stellar evolution
- stellar feedback

Star formation gas ejection
The “Bathtub” Model

Change in Cold Gas Reservoir

\[
\frac{dM_{\text{gas}}}{dt} = \epsilon_{\text{cold}} f_{\text{baryon}} \frac{dM_{\text{halo}}}{dt} - (1 - f_{\text{recycle}} + f_{\text{outflow}}) \frac{dM_{\text{star}}}{dt}
\]

Accretion Rate \( \propto \) Halo Growth Rate

\[
\frac{dM_{\text{halo}}}{dt} \propto \mathcal{M}_{\text{halo}}^{1.1} (1 + z)^{2.2}
\]

Gas Consumption Rate \( \propto \) Star Formation Rate

\[
\frac{dM_{\text{star}}}{dt} = \text{SFR} = \epsilon_{\text{SF}} \frac{M_{\text{gas}}}{\tau_{\text{dyn}}}
\]

\( \leftrightarrow \) Halo Growth Rate from Simulations

\( \leftrightarrow \) Star Formation Law

\( \leftrightarrow \) Gas Consumption Rate

\( \leftrightarrow \) Ejection out of halo
Stars form because of gravitational collapse of gas clouds, hence:

\[ \text{SFR} = \frac{\varepsilon_{\text{SF}}}{t_{\text{SF}}} \frac{M_{\text{gas}}}{\text{yr}} \]

- **\( \varepsilon_{\text{SF}} \)**: fraction of mol. gas involved in SF
- **\( t_{\text{SF}} \)**: SF timescale

The data on the left show for normal SFGs:

\[ \frac{t_{\text{SF}}}{\varepsilon_{\text{SF}}} \approx 1.5 \text{ Gyr} \]

(\( \varepsilon_{\text{SF}} \approx 0.01 \) for \( t_{\text{SF}} = 15 \text{ Myr} \))
The Cold Gas Accretion Efficiency

Behroozi+10

~3%

mass range when $\epsilon \neq 0$

Milky Way Halo
The Cold Gas Accretion Efficiency

\[
\frac{dM_{\text{gas}}}{dt} = \varepsilon_{\text{cold}} f_{\text{baryon}} \frac{dM_{\text{halo}}}{dt}
\]

- Mass range when \( \varepsilon \neq 0 \)
- \( 10^{11} \) to \( 10^{12.3} \) M\(_{\text{Sun}}\)

- SNe ejection
- Shock heating

Epsilon Cold

Halo Mass
The Cold Gas Accretion Efficiency

Tacchella+2015, Dekel & Birnboim 2006

Diagram showing the relationship between $M_{\text{vir}}$ [M$_{\odot}$] and redshift, with contours indicating hot halo and cold streams in the hot halo.
When all the gas come in hot: drain the tub

When all the gas come in hot: drain the tub

\[
\frac{dM_{\text{gas}}}{dt} = \epsilon_{\text{cold}} \frac{dM_{\text{baryon}}}{dt} - (1 - f_{\text{recycle}} + f_{\text{outflow}}) SFR
\]

\[
SFR = \frac{M_{\text{gas}}}{\tau_{\text{dyn}}} \quad \text{(Kennicutt – Schmidt law)}
\]

when \( \epsilon_{\text{cold}} = 0 \) we have:

\[
\frac{dSFR}{dt} = -\frac{\epsilon_{\text{SF}} (1 - f_{\text{recycle}} + f_{\text{outflow}})}{\tau_{\text{dyn}}} SFR
\]

Solving this equation, we get an exponentially declining SFR:

\[
SFR \propto \exp\left( -\frac{t}{\tau} \right) \quad \text{and} \quad \tau = \frac{\tau_{\text{dyn}}}{\epsilon_{\text{SF}} (1 - f_{\text{recycle}} + f_{\text{outflow}})}
\]
Predicted Star Formation History

- Grey region: efficient cold gas accretion $10^{11} < M_{\text{Halo}} < 10^{12.3} M_\odot$
- Gas accretion history of a $10^{12.6} M_\odot$ halo (mass at $z = 0$)
- Star formation history from the continuity equation:
  1. Once the halo crosses the minimum mass ($10^{11} M_\odot$), the SFR rapidly rises to reach a steady state;
  2. As the halo mass reaches $10^{12.3} M_\odot$, cold gas accretion is choked and the SFR starts to decline with an e-folding time of 2-3 Gyr ($= 2 \tau_{\text{SF}}/\epsilon_{\text{SF}}$).

Bouche+2010, Cattaneo+2006
Dekel & Birnboim 2006
Cosmic star formation peaked when the universe was only 3 billion years old. It declined by 10x in the second half of the universe’s life. SFR = Star Formation Rate.

The Cosmic Star Formation History

<table>
<thead>
<tr>
<th>Age of the universe [Gyr]</th>
<th>Cosmic SFR Density [$M_{\odot} \text{yr}^{-1} \text{Mpc}^{-3}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7</td>
<td>13.9</td>
</tr>
<tr>
<td>1.6</td>
<td>6.0</td>
</tr>
<tr>
<td>3.4</td>
<td>3.4</td>
</tr>
<tr>
<td>13 Gyr ago</td>
<td>0.7</td>
</tr>
<tr>
<td>7 Gyr ago</td>
<td>0.7</td>
</tr>
<tr>
<td>Now</td>
<td>13 Gyr ago</td>
</tr>
</tbody>
</table>

Behroozi+2012
The Decline of Molecular Gas Fraction

Isbell, Xue, Fu 2018: Using Tully-Fisher Relation to Measure Gas Fractions
Challenge I: Rapid build-up of the red sequence

**Red Sequence Formation**

- **Early Completion:**
  Most of the stellar mass in the red sequence is already in place by \( z = 1 \)

- **Rapid Build-Up:**
  Stellar mass density increased more than 20x (\( = e^3 \)) in just 2.5 Gyr \((1 < z < 2)\). So the e-folding time for the mass growth is 1 Gyr.
Color bimodality at high-redshift requires rapid quenching.

The rapid built-up of the red sequence requires rapid decline of SFR:

Red-sequence e-folding timescale of \(~1 \text{ Gyr}\) indicates an SFR e-folding time \(~0.2 \text{ Gyr}\), because SFR must decline by 100 times (\(~5\) e-folding, \(e^5 = 150\)) for a galaxy to cross the green valley.

This is \(10x\) shorter than the gas exhaustion time \(\sim 2 \text{ Gyr}\)!

This is not draining, but quenching!
Challenge II: Submillimeter Galaxies (SMGs)

Submm (850 μm)

- 14010+0253
- 14009+0252
- 14009+0252
- 14011+0252
- cD galaxy

Optical Image overlaid with submm contours

- 14010+0253
- 14009+0252
- 14011+0253
- cD galaxy

Barger+98, Smail+98, Eales+99, Ivison+00
SMG = Submillimeter Galaxies

Grey region: efficient cold gas accretion in halos with $10^{11} < M_{\text{Halo}} < 10^{12.3} M_\odot$

Green region: star formation tracks of all halos

The SFRs of SMGs appear too high for any halos at their observed epoch.
How do we solve these problems?

Better and more observations :}
Submm Surveys with Herschel

2010, Herschel, 16 deg$^2$ in 16 hours

Size of the Moon

1998, JCMT, 50 hours

2010 Herschel
Brightest Submillimeter Sources are Either Extremely Luminous or Lensed

Negrello+(2010)
Efficient Selection of Strongly Lensed SMGs

Blain (1996), Negrello et al. (2007), Wardlow et al. (2013)
Multi-wavelength Follow-up Observations

Herschel

High-Resolution Imaging & Spectroscopy

Keck

SMA/ALMA

JVLA/ALMA

Probing Stars: previous star formation (SF)

Dust: current SF

CO → Molecular Gas: fuel of SF

The Antennae Galaxies
High-Res Imaging w/ Keck Adaptive Optics (AO)

Keck shooting a laser

Bootes01

COSMOS01

G09v1.40

G12v2.30

G15v2.19

Lock01

Lock10

NB.v1.43

XMM01

Calanog, Fu, et al. 2014
Bussmann et al. 2015
Observations of a Strongly Lensed SMG: G12v2.30

Planck 550 µm

Herschel 250-500 µm

Fu+2012b

Gas

Dust

1 arcsec
Source Plane Morphologies: Molecular Gas, Dust, and Stars

Fu+2012b
HXMM01: A Hyper-Luminous SMG Merger at z=2.3

Panel (a) shows the highest resolution images of HXMM01. The background false three-color image combining 250 (blue), 350 (green), and 500 (red) for JVLA, and the Keck contours are at +5, +8, +11 for JVLA, and +3, +4, +6, and +8 for SMA, respectively. HXMM01 is the brightest source in the image.

The two major components of HXMM01 (X01N and X01S) and their jets and clumps are drawn at +3, +4, +6, and +8. The dust to gas energy ratio for SMA is 0.77, where the rms noise is again the rms for SMA, and 0.83 for the JVLA.

The shapes at the lower left show the dust continuum at 250, 350, and 500 microns, and the ionized gas at 880 microns for the SUBMillimeter Array (SMA) and JVLA images. We detect a significant enhancement in the star formation activity compared to the rest of HXMM01. This clump could also label the southern part of X01S as a "clump" because of its enhanced star formation activity.

A Clump with an offset of 0.54 arcsec is seen at X01S. The SMA and JVLA contours are at +5, +8, +11 for SMA, and +3, +4, +6, and +8 for JVLA).

Note that there is also a bridge of dust in between X01N and X01S in the SMA and JVLA images. We have excluded it in our stellar mass estimate of X01S. The emission from the Jansky Very Large Array (JVLA) is blue, and the emission from the VLA is red.

HXMM01 is a SMG Merger at z=2.37 arcsec, with 20 kpc length at z=2.307. The two major components of HXMM01 (X01N and X01S) and their jets and clumps are drawn at +3, +4, +6, and +8.
SMG reproduced by cosmological zoom-in simulations (Narayanan+16)
Deep ALMA Observation of HXMM01

0.2" spatial resolution, 40 km/s spectral resolution, 240 GHz, 2.6 hr on-source

Xue, Fu, et al. 2018
Tilted-Ring Modeling of Gas Kinematics

CO $J=7-6$ Position Velocity Diagram

Xue, Fu+2018

Position Velocity Diagram of Contributing Rings
Flat Rotation Curves @ z = 2.3

\[
V_{\text{rot}} \quad [\text{km/s}]
\]

\[
R \quad [\text{kpc}]
\]

\[
\theta \quad [\text{arcsec}]
\]

Xue, Fu+2018

comp. a

comp. b
Dynamical upper limits on the CO-H$_2$ conversion factor

\[ \alpha_{\text{CO, limit}} = \frac{M_{\text{dyn}}}{L'_{\text{CO}}} (\langle R \rangle) \]  

\[ [M_\odot (K \text{ km s}^{-1} \text{pc}^2)^{-1}] \]

\[ \theta \text{ [arcsec]} \]

\[ R \text{ [kpc]} \]

Xue, Fu+2018

MW
Kennicutt-Schmidt Relation

- Stars form because of gravitational collapse of gas clouds, therefore:
  \[ \Sigma_{\text{SFR}} = \epsilon_{\text{SF}} / t_{\text{SF}} \Sigma_{\text{gas}} \]
  or:
  \[ \text{SFR} = \epsilon_{\text{SF}} / t_{\text{SF}} M_{\text{gas}} \]

- The data on the left show for normal SFGs:
  \[ t_{\text{SF}} / \epsilon_{\text{SF}} \sim 1.5 \text{ Gyr} \]

for starbursts:
  \[ t_{\text{SF}} / \epsilon_{\text{SF}} \sim 0.1 \text{ Gyr} \]

Fu+13, Daddi+09, Genzel+10, Hodge+12
Solutions to the “SMG” Problem

✗: Efficient cold gas accretion continues in $10^{13} \, M_\odot$ halos. disagrees w/ hydro-dynamical simulations and over-produce massive galaxies and SMGs

✓: Burst: Star formation efficiency increases 10x in $10^{13} \, M_\odot$ halos. most likely

✗: Burst: Star formation efficiency increases 10x in $10^{12} \, M_\odot$ halos disagrees w/ clustering results
Suppose SMGs live in dark matter halos with $12.5 < \log(M_{\text{halo}}/M_{\odot}) < 13.5$ and $2 < z < 3$, the space density of such halos is $1.1 \times 10^{-4}$ Mpc$^{-3}$.

Average lifetime of the SMG phase is $\sim 200$ Myr (the gas exhausting timescale, $2 M_{\text{gas}}/SFR$).

Universe aged by 1.2 Gyr between $2 < z < 3$.

So if every such halo goes through an SMG phase, the expected space density of SMGs is:

$1.8 \times 10^{-5}$ Mpc$^{-3} = 1.1 \times 10^{-4} \times (200/1,200)$

agreeing with the observed space density of SMGs:

$2 \times 10^{-5}$ Mpc$^{-3}$ at $2 < z < 3$.
SMGs have ~10x higher SF efficiency than normal galaxies, i.e., they are massive starbursts.

Starbursts can stop star formation by rapidly exhausting the gas reservoir, providing a quenching mechanism to turn blue starforming galaxies into red passive galaxies.

Starbursts are a universal phase in the formation of massive red galaxies. All galaxy formation models should be able to reproduce this important phase.

What triggers the high star formation efficiency? Why every massive galaxy goes through a burst phase?
How do we solve the remaining problems?

Better and more observations :)
Future IR/Submm Telescopes
Put this local interacting luminous IR Galaxy NGC 6090 to $z=4.0$, and place a lensing galaxy at $z=1.5$.

- Seeing: 0.5 arcsec
- HST at 2 $\mu$m: 0.2 arcsec
- JWST at 2 $\mu$m: 0.077 arcsec
- TMT at 2 $\mu$m: 0.017 arcsec

Power of Lensing + JWST/TMT
Take-Home Messages

• Massive starbursts are critical for our understanding of galaxy evolution: they likely represent a transitional phase between blue star-forming galaxies and red dead galaxies.

• Herschel and existing facilities have revolutionized this field, and its legacy will be carried on by ALMA and future observatories like the JWST.

• In the next decade, observations will address the nature of starbursts by resolving star-forming regions and tracing gas accretion through the cosmic web (in both absorption and emission).