15.1 Galaxy Formation: Introduction
Galaxy Formation

• The early stages of galaxy evolution - but there is no clear-cut boundary, and it also has two principal aspects: assembly of the mass, and conversion of gas into stars

• Must be related to large-scale (hierarchical) structure formation, plus the dissipative processes - it is a very messy process, much more complicated than LSS formation and growth

• Probably closely related to the formation of the massive central black holes as well

• Generally, we think of massive galaxy formation at high redshifts (z ~ 3 - 10, say); dwarfs may be still forming now

• Observations have found populations of what must be young galaxies (ages < 1 Gyr), ostensibly progenitors of large galaxies today, at z ~ 5 - 7

• The frontier is now at z ~ 7 - 20, the so-called Reionization Era
A General Outline

• The smallest scale density fluctuations keep collapsing, with baryons falling into the potential wells dominated by the dark matter, achieving high densities through cooling
  – This process starts right after the recombination at $z \sim 1100$

• Once the gas densities are high enough, star formation ignites
  – This probably happens around $z \sim 20 - 30$
  – By $z \sim 6$, UV radiation from young galaxies reionizes the universe

• These protogalactic fragments keep merging, forming larger objects in a hierarchical fashion ever since then

• Star formation enriches the gas, and some of it is expelled in the intergalactic medium, while more gas keeps falling in

• If a central massive black hole forms, the energy release from accretion can also create a considerable feedback on the young host galaxy
Recipe for Galaxy Formation

Gas flows from intergalactic medium

Potential well formed by gravity of (primarily) dark matter
An Outline of the Early Cosmic History

(illustration from Avi Loeb)

↑ Recombination: Release of the CMBR
↑ Dark Ages: Collapse of Density Fluctuations
↑ Reionization Era: The Cosmic Renaissance
↑ Galaxy evolution begins
Physical Processes of Galaxy Formation

• Galaxy formation is actually *a much messier problem than structure formation*. In addition to gravity and build-up of host dark halos (fairly well understood) we need to add:
  – Shock heating of gas
  – Cooling of gas into dark halos
  – Formation of stars (also not a well understood process!) from the cold gas
  – The evolution of the resulting stellar population
  – Feedback processes generated by the ejection of mass and energy from evolving stars
  – Production and mixing of heavy elements (chemical evolution)
  – Effects of dust obscuration
  – Formation of black holes at galaxy centers and effects of AGN emission, jets, etc.

… etc., etc., etc.
What is a Protogalaxy?

Not a very well defined answer; some possibilities:

• Galaxy in the first X % or Y yrs of its life (X=?, Y=?)
• Galaxy which has formed X % of its stars (X=?)
• Galaxy which has assembled X% of its final mass (X=?)
• Initial density fluctuation which has not formed any stars yet
• Galaxy at a very high redshift $z > Z$ (Z=?)

… etc., etc.

• Generally we think of the progenitors of massive galaxies today, roughly in the first Gigayear of their life, i.e., at $z > 6ish$
• We certainly expect vigorous star formation to be occurring, and therefore a luminous object
The Evolving Dark Halo Mass Function (Press-Schechter)

Hierarchical merging produces ever more massive halos as the time goes on.
Via Lactea Simulation

z=0.0

80 kpc
Predicted vs. Observed

SNe Feedback

CDM simulations

Galaxy luminosity fct

$\alpha = -1.21$

$\phi_* = 2.5 \times 10^{-14}$

$M_* = 1.31 \times 10^{11}$

Cooling & AGN Feedback (QSOs)
SN and AGN Feedback Modified the Halo Mass Function

Finkelstein 2015
Energy Release From Forming Galaxies

Galaxies collapse and cool. The release of the binding energy is:

\[ |E_{\text{bind,gal}}| \simeq M_{\text{cool}} \left( V_{3d}^2 \right) \simeq \]

\[ \simeq 1.2 \times 10^{59} \text{erg} \times \left( \frac{M_{\text{cool}}}{10^{11}M_\odot} \right) \left( \frac{V_{3d}}{250 \text{km s}^{-1}} \right)^2 \]

where \( M_{\text{cool}} \) is the total mass which can cool radiatively.

Binding energy was also released by collapsing protostars, and is of a comparable magnitude:

\[ |E_{\text{bind,\star}}| \simeq G M_{\Sigma_\star} \left( \frac{M_{\star}}{\langle R_\star \rangle} \right) \simeq \]

\[ \simeq 4 \times 10^{58} \text{erg} \times \left( \frac{M_{\Sigma_\star}}{10^{10}M_\odot} \right) \left( \frac{\langle M_{\star} \rangle}{M_\odot} \right) \left( \frac{R_\odot}{\langle R_\star \rangle} \right) \]

where \( M_{\Sigma_\star} \) is the total mass converted to stars in the PG phase, \( \langle M_{\star} \rangle \) is the average star mass, and \( \langle R_\star \rangle \) is the average star radius.
Energy Release From Forming Galaxies

Probably the most important energy source in PGs was the nuclear burning in initial starbursts:

\[ E_{\text{nucl}} \approx \epsilon M_{\Sigma*} c^2 \Delta X \approx 10^{60} \text{erg} \left( \epsilon/0.001 \right) \left( M_{\Sigma*}/10^{10} M_\odot \right) \left( \Delta X/0.05 \right) \]

where \( M_{\Sigma*} \) is the total mass burned in stars in the PG phase, \( \epsilon \approx 1 \text{ Mev}/m_p c^2 \approx 0.001 \) is the average net efficiency of nuclear reactions in stars, and \( \Delta X \approx \Delta Z + \Delta Y \approx 0.05 \) is the fraction of the hydrogen converted to helium and metals.

Note: the mean metallicity of old stellar populations is \( \sim \) Solar, i.e., about 1.7% by mass; and you get \( \sim 3-5 \) g of He (\( \Delta Y \)) for each 1 g of metals (\( \Delta Z \)) produced in stellar burning.

Finally, early active galactic nuclei may have been important contributors to the energy budget in at least some, and possibly all PGs. Their energy release could have rivaled other mechanisms. Taking a rough guess for the average luminosity \( \langle L_{\text{bol}} \rangle \) and the duration of the active episode \( \Delta t \):

\[ E_{\text{AGN}} \sim \langle L_{\text{bol}} \rangle \Delta t \approx 1.2 \times 10^{60} \text{erg} \left( \langle L_{\text{bol}} \rangle/10^{10} L_\odot \right) \left( \Delta t/10^8 \text{yr} \right) \]
15.2 Galaxy Formation: Observations
Expected Observable Properties of PGs

- We expect a release of $\Delta E \sim 10^{60}$ ergs from a typical proto-elliptical (or a large bulge); but over what time scale?
  - The starburst time scale of $\sim 10^7 - 10^8$ yrs
  - The free-fall time scale of $\sim 10^8$ yrs
  - The merging time scale of $\sim 10^9$ yrs

- Since luminosity is $L \sim \Delta E/\Delta t$, we estimate typical
  
  $$L_{PG} \sim 10^{11} - 10^{12} L_\odot,$$

  or absolute magnitudes $M \sim -22$ to -25 mag

- Given the luminosity distances to $z \sim 6 - 8$, the expected apparent magnitudes are in the range $\sim 26$ to 30 mag

- A few % of the total energy is in recombination lines, e.g., Ly$\alpha$

- But the Big Question is: is this luminosity obscured by dust?
  - No: optical surveys
  - Yes: sumb-mm/FIR surveys; use molecular lines, e.g., CO
Emission Line Search Methodologies

Slitless spectroscopy:
Large volume, but low S/N (~ depth)

Long-slit spectroscopy:
Small volume, large redshift range, good depth

Narrow band imaging:
Moderate volume, small redshift range, good depth
Narrow-Band Imaging

A greatly increased contrast for an object with a strong line emission
Long-Slit Spectroscopy + Serendipity

![Graph showing spectral lines and designation](image)
A Galaxy at $z \sim 7$

**IOK-1 at $z = 6.96$**
(Iye et al. 2006; Subaru)
Discovered using narrow band imaging technique
The Lyman-Break Method

Absorption by the interstellar and intergalactic hydrogen of the UV flux blueward of the Ly alpha line, and especially the Lyman limit, creates a continuum break which is easily detectable by multicolor imaging.
Photometric Redshifts

Using the combination of 4 optical and 4 infrared filters, the redshifts of individual galaxies can be estimated for systems well beyond current spectroscopic reach.

(from R. Ellis)
Color-Selected Candidate High-z Galaxies

7 star-forming galaxies located 8.5<z<12

5σ detections in (160W+140W+125 W) stack (m_{AB} < 30.1)

2σ rejection in ultradeep F105W (m_{AB} > 31.0)

2σ rejection in ACS BViz (m_{AB} > 31.3)


z=11.9? 380 Myr

z=9.5 520 Myr

z=9.5 520 Myr

z=8.8 570 Myr

z=8.8 570 Myr

z=8.6 590 Myr

z=8.6 590 Myr
GN-z11: A Galaxy at $z = 11.1$?
Star formation density of LBGs

Monotonically declining population to $z \sim 6$ and beyond

Drop of $\times 8$ in UV luminosity density over $2 < z < 6$

However, even some galaxies at $z > 6$ seem to have been forming stars for a while, indicating a very early onset of galaxy formation.

Lensed arc galaxy at $z \sim 6.7$ (?) behind A2218

(Egami et al. 2005)
• **Strong, bias-driven clustering** of the first luminous sources is generally expected in most models.

• There is a lot of evidence that this does occur at $z \sim 4 – 6$, from clustering of Ly$\alpha$ galaxies, to clustering of Ly-break galaxies around high-z QSOs.

• This may lead to a *clumpy reionization*, which among other things would produce a rise in the cosmic variance of the IGM transmission in the approach to reionization.

• There is some evidence that this indeed does occur, from the spectra of $z \sim 6$ QSOs - and this may help improve our understanding of the final phases of reionization.
Evidence for a Strong Biasing at High $z'$'s

- LBGs at $z \geq 3$, $\sim$ Mpc scales (Steidel, Adelberger, et al.)
- Clustered QSO companions at $z \sim 4 - 6$, scales $\sim 0.1 - 1$ Mpc (Djorgovski et al., Stiavelli et al., etc.); and also radio galaxies at similar $z'$'s (Venemans et al.)
- Clustered Ly$\alpha$ and LB galaxies at $z \sim 4.9 - 5.7$, scales $\sim$ a few Mpc (Shimasaku et al., Ouchi et al., Hu et al., etc.)
- Estimated bias factors $b \sim 3 - 6$, but could be as high as $\sim 10 - 30$!
Protoclusters Around $z \sim 6$ QSOs?

Evidence for an excess of color-selected galaxies in the fields of $z \sim 6$ QSOs

Examples of color-selected candidates

Spectroscopic confirmations

15.3 Reionization Era: The First Stars
The First Stars

Gas infall into the potential wells of the dark matter fluctuations leads to increased density, formation of H$_2$, molecular line cooling, further condensation and cloud fragmentation, leading to the formation of the first stars.

*Bromm et al.* *Abel et al.*
Primordial Star Formation: a Top-Heavy IMF?

Expected in all modern models of Pop III star formation, characteristic $M \sim 10^2 - 10^4 M_\odot$ (due to a less efficient cooling of protostellar clouds)

$z=18.2$

Abel et al.

Bromm et al.
Population III Stars: Hot and Luminous

They can easily reionize the universe by $z \sim 6$
Population III Supernovae

- Early enrichment of the protogalactic gas
- Transition to the “normal” Pop II star formation and IMF when the metallicity reaches a critical value $Z_{\text{crit}} \sim 10^{-3.5} Z_\odot$

Simulated Pop III SN shell after $\sim 10^6$ yr

Distrib. of metals (red)

(from Bromm et al. 2003)
The Fate of Supermassive Pop. III Stars

(Heger, Woosley, et al.)

GRB!
GRB 050904 at $z = 6.295$

A preview of the more distant, Pop. II flashes to come!

(Kawai et al. 2006, Haislip et al. 2006, Tagliaferri et al. 2006, etc.)
GRB 090423 at $z \sim 8.2$ (?)

The current record holder – no details available yet
Population III Stars

- They may have formed in large numbers as early as $z \sim 20 - 30$, and (partly?) reionized the universe, as WMAP data indicate.
- However, their feedback may have extinguished the star formation in their hosts, possibly leading to a (partial?) recombination.
- Then the formation of Pop. II stars may have reionized the universe again, ending the process at $z \sim 6$, as QSO data indicate.

(Bromm & Loeb)
Simulations of the Cosmic Reionization

(from P. Madau et al.)
15.4 Reionization Era: The Cosmic Renaissance
The Cosmic Reionization Era
(The Cosmic Renaissance)

DM Halos Form

- Pop III Stars, Early BH
- Pop II +OMR, SMBH
- Evolution & Growth
- Pop I …

Time since the Big Bang (years)

- ~ 300 thousand
- ~ 500 million
- ~ 1 billion
- ~ 9 billion
- ~ 13 billion
Simulations of the first stars and galaxies

(Abel, Wise, et al.)
The Gunn-Peterson Effect

Even a slight amount of neutral hydrogen in the early IGM can completely absorb the flux blueward of Ly\(\alpha\)

The Gunn-Peterson (1965) optical depth to Ly\(\alpha\) photons is

\[
\tau_{\text{GP}} = \frac{\pi e^2}{m_e c} f_\alpha \lambda_\alpha H^{-1}(z) n_{\text{HI}},
\]

where \(f_\alpha\) is the oscillator strength of the Ly\(\alpha\) transition, \(\lambda_\alpha = 1216\ \text{Å}\), \(H(z)\) is the Hubble constant at redshift \(z\), and \(n_{\text{HI}}\) is the density of neutral hydrogen in the IGM. At high redshifts,

\[
\tau_{\text{GP}}(z) = 4.9 \times 10^5 \left( \frac{\Omega_{m} h^2}{0.13} \right)^{-1/2} \left( \frac{\Omega_{b} h^2}{0.02} \right) \left( \frac{1 + z}{7} \right)^{3/2} \left( \frac{n_{\text{HI}}}{n_{\text{H}}} \right)
\]

for a uniform IGM. Even a tiny neutral fraction, \(x_{\text{HI}} \sim 10^{-4}\), gives rise to complete GP absorption. This test is only sensitive at the end of the reionization when the IGM is already mostly ionized, and the absorption saturates for the higher neutral fraction in the earlier stage.

(from Fan et al. 2006, ARAA, 44, 415)
Detecting The Cosmic Reionization From High-\(z\) Quasar Spectroscopy
“Gunn-Peterson like” troughs are now observed along all available lines-of-sight at $z \sim 6$
Transmitted Lyα Flux vs. Redshift

(from Fan et al. 2006, ARAA, 44, 415)
QSO Observations Suggest the End of the Reionization at $z \sim 6$

A sudden change in the UV opacity of the intergalactic medium

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**Photoionization Rate**

**Neutral Hydrogen Fraction**

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*Fan et al.*
Substantial Diversity of IGM Absorption Seen Along Different Lines of Sight

Shown here is the IGM transmission over the same redshift window, but along 4 different QSO lines of sight

A Considerable Cosmic Variance Exists in the transmission of the Ly$\alpha$ forest at $z > 5$
Further Evidence for Late Reionization

Rapid decline in abundance of Ly$\alpha$ emitters from $5.7 < z < 6.6$ (Ouchi et al 2010): $x_{HI} \sim 0.1$ at $z = 6.6$?

Damping wing of Ly$\alpha$ in $z=7.085$ QSO: $x_{HI} > 0.1$ at $z \sim 7$? (Mortlock et al. 2011, Bolton et al. 2011)
CMB Constraints on Reionization

WMAP+eCMB, Hinshaw et al (2012): $\tau = 0.084 \pm 0.013$
consistent with an instantaneous reionization at $z = 10.3 \pm 1.1$
But also consistent with an extended reionization from $z \sim 20 - 25$ to $z \sim 6$ (more realistic)
Planck Collaboration 2016: $\tau = 0.058 \pm 0.012$ for instantaneous reionization model, $z = 8.2 \pm 1.1$ favored
Upper limit to the width of reionization period: $\Delta z < 2.8$

CMB Constraints on Reionization

Data points from QSOs, Ly-alpha emitters and Ly-alpha absorbers
Putting It All Together

Based on the Hubble Ultra Deep Field analysis (Robertson et al. 2013)
Looking Even Deeper: The 21cm Line

We can in principle image H I condensations in the still neutral, pre-reionization universe using the 21cm line. Several experiments are now being constructed or planned to do this, e.g., the Mileura Wide-Field Array in Australia, or the Square Kilometer Array (SKA).

(Simulations of $z = 8.5$ H I, from P. Madau)