The First Galaxies (z>5)

(What we can learn about their early build-up and contribution to reionization from the observations)

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Galaxy Formation, An international conference
July 22, 2011 (Durham, UK)
Installation of the WFC3 camera on HST

- 6.5x larger field-of-view than previous camera (NICMOS)
- 3-4x more sensitive than previous camera
- 2x higher spatial resolution (not undersampled)

Many New Facilities to Push High-Redshift Science Forward
Many New Facilities to Push High-Redshift Science Forward

Wide-area near-IR imagers from ground, i.e., HAWK-I on VLT

-- very large field of view (8' x 8')
-- very sensitive (reaches to ~27 mag in ~10 hours)
Many New Facilities to Push High-Redshift Science Forward

Ultra Wide-area surveying telescopes like VISTA
Many New Facilities to Push High-Redshift Science Forward

Installation of the WFC3 camera on HST

-- 6.5x larger field-of-view than previous camera (NICMOS)
-- 3-4x more sensitive than previous camera
-- 2x higher spatial resolution (not undersampled)

~40x more efficient for exploring high redshift universe
Substantial progress in # of high-redshift galaxies discovered when universe was < 900 million years old i.e., redshift > 6.5

PRE-2009 (PREVIOUS GENERATION INSTRUMENTS)   NEW CAMERA (WFC3/IR)

~10-15 galaxies (< 2009)   ~20 galaxies (1st week of observations)   >100 galaxies (now)
### Published Samples of z>6.5 Galaxies (photometric selection from new WFC3/IR data)

<table>
<thead>
<tr>
<th>Authors</th>
<th>Redshift Range</th>
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<tbody>
<tr>
<td>Bouwens et al. 2011a,b</td>
<td><del>73 z</del>7</td>
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<td></td>
<td><del>59 z</del>8</td>
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<td></td>
<td><del>1 z</del>10</td>
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<td>Finkelstein et al. 2010</td>
<td><del>41 z</del>6-9</td>
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<tr>
<td>McLure et al. 2011</td>
<td><del>60 z</del>6-9</td>
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<tr>
<td>Wilkins et al. 2011; Lorenzo et al. 2011</td>
<td><del>44 z</del>7</td>
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<td><del>24 z</del>8</td>
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<tr>
<td>Grazian et al. 2010</td>
<td><del>42 z</del>7</td>
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<td>Yan et al. 2010</td>
<td><del>20 z</del>7</td>
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<td><del>20 z</del>10</td>
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Published Spectroscopically confirmed z>6.5 galaxies

Vanzella et al. (2011)
2 z~7

Ono et al. (2011)
2 z~7

Schenker et al. (2011)
3 z~7

Iye et al. 2011
1 z~7

~8 spectroscopically confirmed z~7 galaxies

(since z~7 galaxies tend to be spectroscopically confirmed only through the detection of Lyα emission, the small # of confirmations is not an important concern)
Why are studies of z>5 galaxies interesting?

-- It is when galaxies first form...
(halos of L* and sub-L* galaxies built up from z~30+ to z~3)

-- It is when the universe was reionized...
(galaxies are most likely driver, so by studying the formation of first
galaxies perhaps we can gain insight)

-- It is when metals are first produced in significant abundance
(could result in changes in various spectral properties, e.g., IMF, dust properties)
How fast do galaxies build-up and grow?
Quantifying Galaxy Build-up using The Luminosity Function of Galaxies

In rest-frame UV -- since easiest to quantify observationally and likely proportional to stellar mass...
What does the galaxy LF at $z>5$ look like?
($z\approx7$ LF from Bouwens et al. 2011; Ouchi et al. 2011)

Bouwens et al. 2010a,b; Ouchi et al. 2009; see also Castellano et al. 2010
What does the galaxy LF at z>5 look like?
(comparison of many different LFs)
How rapidly does the UV LF evolve from $z \sim 8$ to $z \sim 3$?
(from Bouwens et al. 2011; but similar results from other groups)

Bouwens et al. 2011
How rapidly does the UV LF evolve from z~8 to z~3?  
(Bouwens et al. 2011; but similar results from other groups)

Results from other teams similar -- with some teams (McLure et al. 2010; Castellano et al. 2010) favoring more evolution in $\phi^*$

Very uniform evolution of UV LFs with redshift

68% and 95% confidence intervals

Bouwens et al. 2011
How early in the universe can we begin tracing galaxy buildup?

Can we do this at $z \sim 10$?

(500 Myr after Big Bang)
Extensive efforts to identify z~10 sources in the first half of the HUDF WFC3/IR data

~23 weak z~10 candidates in early data ("lottery tickets")

Yan et al. (2010); Bouwens et al. (2010, arXiv)
Efforts continued after 100% of the HUDF WFC3/IR data were available. Single high-quality $z\sim10$ Candidate

1st Year (~50%) + 2nd year (~50%) HUDF WFC3/IR data

Bouwens et al. 2011; Oesch et al. 2011; other teams (e.g. Haojing Yan, Steve Wilkins) find candidate too
Is it probable a z~10 galaxy has been found?

-- z~10 galaxy candidate in HUDF is plausible
  Disappears at < 1.4 microns, deep ~100 hour IRAC data over HUDF
demonstrate source is blue (Bouwens et al. 2010; Oesch et al. 2011)

-- z~10 candidate is not 100% secure yet (obviously!)
  While it is detected (>2.5σ) in 4 independent splits of the observations
  and >5.5σ, there is a small probability it could be spurious
What do z~10 searches teach us about galaxy build-up?

Search over HUDF, HUDF parallel fields, CDF-South (ERS+CANDELS)

Oesch et al. 2011 search (1 z~10 candidate)

Observed LF is even lower than extrapolation: accelerated evolution at z>8?

Oesch et al. 2011; but see also Bouwens et al. 2011
Galaxy LF grows rapidly...

But how quickly do *individual* galaxies build up at early cosmic times?

Does it occur regularly along a star-forming sequence?
Theoretically, a tight relationship between galaxy properties and galaxy mass/luminosity is expected. According to Dave et al. (2006), metallicity is correlated with stellar mass. However, results from other teams, such as Nagamine, also need to be considered.
Theoretically, a tight relationship between galaxy properties and galaxy mass/luminosity is expected.

Dave et al. 2006
Do we find a similarly tight relationship between observables as a function of mass?

Do we find a tight color-magnitude relation in high redshift galaxies?
WFC3/IR allows us to probe the UV colors of $z \geq 4$ galaxies to high accuracy.
Do we find a similarly tight relationship between observables as a function of mass?

Gonzalez et al. 2011; Stark et al. 2009
Sequence of Star-forming Galaxies

Labbe et al. 2010

SFR vs Stellar Mass

McLure et al. 2011

Stellar Mass vs Stellar Mass

Bouwens et al. 2011

SFR (dusted corrected)

see also Stark et al. 2009
Once you have the LFs, SFR vs. stellar mass relationships, dust properties, and taking galaxies at a given part of the LF and integrating the evolution of galaxies forward, can we match the stellar mass in galaxies at late times?

While this works using the data and assumptions adopted by Papovich et al. 2011, it seems quite likely that this will need to be revisited based on future data...

as we determine the masses, dust properties, duty cycles, LFs, ... better

This will likely be an important activity going forwards...

Papovich et al. 2011
We can of course use the much better constraints on UV colors -- or UV continuum slopes of galaxies -- to update the SFR density or specific SFR evolution?
Integrating the UV LFs, we derive the SFR density

(Illustrative results from Bouwens et al. 2011: similar results from other groups)
An interesting puzzle has been the mild evolution of SSFR(z)

Improved UV slopes imply higher dust extinction

Bouwens et al. 2011; Gonzalez et al. 2010; Stark et al. 2009; Daddi et al. 2007, 2009; Noeske et al. 2007
Are very low luminosity galaxies at z>6 extraordinarily blue (providing evidence for different stellar pops)?

- Suggested real uncertainties are larger (Finkelstein et al. 2010)

- Bouwens et al. 2010 error bars consistent with Finkelstein et al. 2010 errors when using similar sample sizes and binning...

- Blue colors artifact of selection biases (Dunlop et al. 2011)

Early finding from WFC3/IR data (Bouwens et al. 2010)
Dunlop et al. (2011) suggested $\beta = -3$ measurement was likely due to a bias.

Why would we expected the biases in $\beta$ to be relatively small? Observations used for (1) selecting sources and (2) measuring $\beta$ are largely independent (particularly in the lower redshift samples).
Old versus new measurements of the UV-continuum slope $\beta$ at $z\sim 7$

It would that what we are seeing at $z\sim 7$ is just another example of the dust-mass relationship seen at lower redshift... and the early $\beta$ measurements may have simply been subject to random errors

New measurements in faint $z\sim 7$ samples suggest $\beta \sim -2.7$ (Bouwens et al. 2011)

Bouwens et al. 2010, 2011; Wilkins et al. 2011
Do we find a similarly tight relationship between observables as a function of mass? (results from Bouwens et al. 2011)

Bouwens et al. 2011; see also Bouwens et al. 2009, 2010; Wilkins et al. 2011; Dunlop et al. 2011
Reionization of the Universe

When? Are galaxies responsible?
Reionization of the Universe

Can we learn anything about when reionization occurs -- due to the effects of a more neutral IGM in weakening Ly$\alpha$ emission from galaxies?

-- Neutral hydrogen in IGM will weaken the Ly$\alpha$ emission from galaxies

-- The fraction of Ly$\alpha$ emitters in a high-redshift galaxy population should decrease as the universe becomes more neutral.

(Slide adapted from one by Dan Stark)
Reionization of the Universe

Neutral hydrogen in IGM will weaken the Lya emission from galaxies

Kashikawa et al. 2011 (but see also Hu et al. 2010; Ouchi et al. 2010)
Schenker et al. 2011 (but see also Pentericci et al. 2011; Ono et al. 2011)

Extrapolating the prevalence of Ly$\alpha$ emitters seen in lower redshift galaxies to $z\sim7$, we would expect 50% to show strong Ly$\alpha$ emission.

Follow-up of $z\sim7$ candidates with spectroscopy shows a prevalence of Ly$\alpha$ emission that is $>5x$ smaller.

Ly$\alpha$ LF shows a substantial drop in ionizing UV from $z\sim5.7$ to $z\sim6.5$

Of course, caution is advised since such changes can also occur due to evolution in the galaxy population...

or even the density of the universe itself.

Kashikawa et al. 2011; Hu et al. 2010; Ouchi et al. 2010; Stark et al. 2010; Schenker et al. 2011; Pentericci et al. 2011; Fontana et al. 2011; Ono et al. 2011
Do galaxies drive reionization?
Can galaxies reionize the universe? (how much light do they produce?)

Bright Contribution is easy...
Faint Contribution is more challenging...

More complicated than this:
- Not UV continuum --> Lyman continuum
- Only Ly-continuum light that escapes...

Can galaxies reionize the universe?
(how much light do they produce?)

More complicated than this:
- Not UV continuum --> Lyman continuum
- Only Ly-continuum light that escapes...

Simply Integrate This
extrapolated component...

$\log_{10} \text{Number / Mpc}^3$
$M_{\text{UV,AB}}$

$-22$  $-21$  $-20$  $-19$  $-18$

-5  0  5  10
Can galaxies reionize the universe?
(how much light do they produce?)

How big is the correction for unseen faint sources?

Very sensitive to faint-end slope...
Can galaxies reionize the universe? (how much light do they produce?)

Correction (for unseen sources) depends very sensitively on faint-end slope
(integrated to -10 AB mag: approximate limiting luminosity expected in many models)

Faint-end slope of UV LF is very important to establish

Bouwens et al. 2011
What are our current constraints on the faint-end slope?

Can galaxies reionize the universe?

(z~7)

\[ \alpha = -1.72 \pm 0.65 \] (Ouchi et al. 2009)

\[ \alpha = -1.77 \pm 0.60 \] (Grazian et al. 2011)

\[ \alpha = -2.00 \pm 0.21 \] (Bouwens et al. 2011)

\[ \alpha = ??? \] (including CANDELS + deeper HUDF)

(z~6)

\[ \alpha = -1.87 \pm 0.14 \] (Su et al. 2011)

\[ \alpha = -1.73 \pm 0.17 \] (Bouwens et al. 2007)
Can galaxies reionize the universe? (how much light do they produce?)

Adopt observed UV LFs and extrapolate to higher redshifts

Other Details:
- Integrate to Very Low luminosities: -10 mag
- Clumping Factor ~3 (Bolton et al. 2005; Pawlik et al. 2009)
- Escape Fraction ~20%

Can we match the Thompson optical depth found by WMAP, \( \tau \sim 0.088 \pm 0.015 \)?

Thomson optical depth
\( \tau \sim 0.066 \)

Bouwens et al. 2011
What are our current constraints on the faint-end slope?

Can galaxies reionize the universe?
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Can we match the Thompson optical depth found by WMAP, $\tau \sim 0.088 \pm 0.015$?

Thomson optical depth $\tau \sim 0.080$

Bouwens et al. 2011
What are our current constraints on the faint-end slope?

Slight evidence for steepening...

Can galaxies reionize the universe?
(how much light do they produce?)

Can galaxies reionize the universe? (how much light do they produce?)

Predicted $\tau_e$ very sensitive to evolution in faint-end slope...

Establish its evolution with redshift...

Bouwens et al. 2011; see also Yan & Windhorst 2004
The First (z>5) Galaxies: What we can learn from the observations

New instrumentation -- especially WFC3/IR -- allows us to very efficiently identify galaxies at high redshift. More than 100 galaxy candidates known at z>6.5. Soon the number will be > 200.

The evolution of the UV LF continues very smoothly from z~8 to z~4, with continued exponential growth in the LF.

One plausible z~10 candidate in current observations. Its volume density is even lower than that expected extrapolating LF evolution to z>8 -- suggesting accelerated evolution.

A tight UV-continuum slope vs. luminosity sequence is found for z~4-7 galaxies. This presumably a mass metallicity relationship.

Current observations support the existence of a sequence of star-forming galaxies at z>4, similar to what is found at lower redshift.

Integrating this forward, one can plausibly match the evolution seen in the stellar masses of galaxies at bright end of LF.

The total flux density in ionizing photons is very sensitive to the faint-end slope. Given current uncertainties in the slope, deeper observations are absolutely necessary.

The faint-end slopes measured at z>=6 are very steep and may steepen towards high redshift. As a result, galaxies may be capable of reionizing the universe.