Galaxy Build-up at Cosmic Dawn: Insights from Deep HST and Spitzer/IRAC Observations

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The history of astronomy is a history of receding horizons.

E. P. Hubble
Unprecedented Galaxy Samples at $z \geq 4$
(from HST’s blank fields only)

Almost 1000 galaxies in the epoch of reionization at $z > 6$
Current frontier: $z \sim 9-10$
The Evolution of the UV Luminosity Function to $z \sim 8$

See also: e.g. Oesch+10a/12, Bouwens+10a,11,12; Bunker+10, Finkelstein+10/14, Wilkins+10/11, McLure+10/13, Yan+12, Bradley+12, ...
The Hubble Frontier Fields: Extending Analyses to Fainter Luminosities

Using HFF dataset, some indication for continued steep increase in LF down to $M_{UV} \sim -13$.

Unclear, how much these LFs can be trusted given uncertainties in high-magnification regions (>10x)

See also: e.g. Atek+15ab, Ishigaki+15, Laporte+15, Castellano+16
Reionization by Faint Dwarf Galaxies

New Planck polarization results find: $\tau_e = 0.058 \pm 0.012$, i.e. $z_{\text{reion}} = 8.2 \pm 1.1$
Consistent with estimates from ultra-faint galaxy population.

Was reionization driven by faint dwarf galaxies? **Likely yes!**

*Caveats: uncertainties in UV LF faint end slope and $f_{\text{esc}}$*

See also: Oesch+09, Bouwens+12, Kuhlen+12, Finkelstein+12, Robertson+13/15

Planck Intermediate Results XLVII

Dashed lines: different extrapolations of UV LFs by Bouwens+15, Robertson+15, Ishigaki+15
Source identification
UV Light / SFRs

ISM Properties
Dust Reemission

Rest-frame Optical
Stellar Masses

Spectroscopic Confirmation
K-band imaging

AGN?
Very Faint, Individually Detected $z \sim 7-8$ Sources

Small area over GOODS-S has 180-220 hour IRAC exposure times (27.4 mag, 3σ)
Ongoing program (GREATS; PI Labbe, 733 hrs) to push full GOODS-S+N Deep to this depth
Extremely Strong Lines are Ubiquitous at $z>6$

At $z\sim6.8$ Spitzer/IRAC [3.6] provides a clean probe of OIII+H$\beta$ lines.

Extremely strong rest-frame EWs reaching over 1000 Å are common at these redshifts!

Needs to be accounted for in SED mass fits.

see also: Schauer&deBarros09, deBarros+14, Shim+11, Labbe+13
Our GSMFs are characterized by a steeper low-mass-end slope of 2012; Duncan et al. 2014; Grazian et al. 2015). All points and lines are converted to a Salpeter IMF. The thick grey lines show dark matter selected sample at GSMF) of González et al. (2011) from WFC3/IR data of the ERS (for within the 1
three, respectively. The uncertainty on our fiducial GSMF includes contributions from both the UV luminosity function uncertainties and our fiducial asymmetric-scatter GSMFs, respectively. The red dotted, red dashed, and red solid lines represent the Schechter fit for the last filled squares, small stars, and red filled circles indicate raw bootstrapped, incompleteness-corrected bootstrapped, constant-scatter, and Const-scatter GSMF

φ

Fig. 9.—

logM = 10.44

α = -1.53

logφ' = -3.52

φ

φ

φ

φ

Song+16

logM = 10.47

α = -1.67

logφ' = -3.87

φ

φ

φ

φ

z ∼ 4

z ∼ 5

z ∼ 6

z ∼ 7

see also: Grazian+15, Duncan+14, Salmon+14, Ilbert+13, Muzzin+13, Gonzalez+11, Lee+12
Rest-Frame Optical Light of z~9-10 Galaxies

Powerful combination of HST and Spitzer to explore most distant galaxies
Stellar Mass Density Evolution to z~10

Luminosity limited SMD estimates at z>4 nicely match up with mass limited studies at z<4.

Are witnessing the assembly of the first 0.1% of local stellar mass density. The first two Gyr are a very active epoch of galaxy assembly.
Increased $z \sim 9-10$ Galaxy Sample: Full CANDELS + BORG

A handful new, bright, bona-fide $z \sim 9-10$ candidates with $H=26.0-26.5$
**Triply Imaged z~10 Candidate in First FF Cluster**

**Zitrin+14**

H = 29.9 mag (de-magnified)  
zphot = 9.8+-0.4  
magnification: 10-11x

strong geometric support of high redshift solution of photo-z

(see also Oesch+15, McLeod+15, Ishigaki+15)
The UV Luminosity Function at the Cosmic Frontier

Including HFF galaxy candidates, now have a quite good estimate of the UV LF at z~10. It lies a factor ~4-5x below the extrapolation from lower redshift trends.

Fast evolution from z~8 to z~10.
Rapid Decline Consistent with Models

Rapid decline in the cosmic SFRD is consistent with most models, but there is a considerable range in predicted evolutions at z>8.

Need to understand this before launch of JWST to plan most efficient surveys!
Spectroscopic Features of High-z Galaxies

Lyα is the most promising feature of high-redshift spectra
Other emission lines very weak, but possible to detect (e.g. Stark+15, 16)

Shapley+03

low-ion IS abs
high-ion IS abs
stellar
nebular em
fine-structure em
H I cm/abs

Finkelstein 16

Year of Discovery
Bright z~8 Galaxies with Spectroscopic Redshifts

Spitzer/IRAC colors allow us to exploit very wide area imaging data to search for rare, ultra-luminous z~8 galaxy candidates with robust photometric redshifts.
Bright z~8 Galaxies with Spectroscopic Redshifts

100% spectroscopic success rate via Lyα detection in such galaxies!
see: Roberts-Borsani+15 (z=7.48), Zitrin+15 (z=8.68), Stark+16 (z=7.15)

EGS-zs8-1 now has a three line redshift z=7.73.
Very high EW CIII] emission
Different Way Forward: Continuum Break Redshifts

If Ly\(\alpha\) disappears, need different technique to measure redshifts: *continuum breaks (as done for QSOs)*

*Note:* at \(z>6\) these are the Ly\(\alpha\) continuum breaks

**Problem:** the background in the NIR is very high from the ground and faintness of galaxies compared to QSOs

Rhoads+13

\[ z_{\text{Ly}\alpha + \text{Ly-break}} = 6.573 \]

Tanvir+09

\[ z_{\text{Ly-break}} = 8.2 \]
HST Grism

Slide Credit: I. Momcheva
HST Grism

FIGS and others...
very bright z~10 sample from Oesch+14 is within reach of the WFC3/IR grism!
Neighbor Contamination in Grism Spectra

Even in a blank field, it’s difficult to identify orientations with minimal contamination. Previous AGHAST spectra heavily contaminated.

Perform full 2D contamination modelling and neighbor subtraction (based on 3D-HST grism pipeline; Brammer+12, Momcheva+15)
Lyman Break Detection at $z=11$

- Overall continuum detection $\sim 5.5\sigma$ at $\lambda > 1.47$ $\mu$m
- Detected at 1-1.5$\sigma$ per resolution element (91 Å)
- Detection in both epochs individually (but at low S/N)
- Break factor ($f_{\text{red}}/f_{\text{blue}}$) of $>3.1$ (2$\sigma$, 500 Å) rules out $z \sim 2$-3 interloper (Maximally old BC03 model at $z=2.7$ a factor of $<2.7$ defined the same way)
- Rule out emission line contaminant
- Best-fit redshift: $z=11.09 \pm 0.10$
The Higher Redshift

The grism data rules out the peak of the previous photometric redshift ($z_{\text{phot}}=10.2$). Is consistent with high-end tail of photo-z and with the photometry.
Better Spectrum Required?

HST TAC comment:
“...the spectrum presented in Oesch et al. (2016) was not convincing...”
Physical Properties of GN-z11

- UV luminosity $\sim 3 \times L^*(z=7)$
- Stellar mass $\sim 10^9 M_\odot$
- SFR$\sim 24 M_\odot/yr$, age$\sim 40$ Myr

Massive galaxy formation well under-way at $z\sim 11$

### Summary

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>R.A.</td>
<td>12:36:25.46</td>
</tr>
<tr>
<td>Dec.</td>
<td>+62:14:31.4</td>
</tr>
<tr>
<td>Redshift $z_{\text{grism}}$</td>
<td>11.09$^{+0.08}_{-0.12}$</td>
</tr>
<tr>
<td>UV Luminosity $M_{UV}$</td>
<td>$-22.1 \pm 0.2$</td>
</tr>
<tr>
<td>Half − Light Radius$^b$</td>
<td>$0.6 \pm 0.3$ kpc</td>
</tr>
<tr>
<td>$\log M_{gal}/M_\odot$</td>
<td>$9.0 \pm 0.4$</td>
</tr>
<tr>
<td>$\log \text{age}/yr$</td>
<td>$7.6 \pm 0.4$</td>
</tr>
<tr>
<td>SFR</td>
<td>$24 \pm 10 M_\odot , \text{yr}^{-1}$</td>
</tr>
<tr>
<td>$A_{UV}$</td>
<td>$&lt; 0.2$ mag</td>
</tr>
<tr>
<td>UV slope $\beta$ ($f_\lambda \propto \lambda^\beta$)</td>
<td>$-2.5 \pm 0.2^d$</td>
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Physical Properties of GN-z11 in Line with Models

The derived physical properties (SFR, mass, and age) of GN-z11 are in very good agreement with expectations from large-volume simulations.
GN-z11 is off the Charts

- Detection of GN-z11 in existing data is quite unexpected, given current models
- Expected to require 10-100x larger areas to find one such bright z~11 galaxy as GN-z11
- Difficult to draw conclusions based on one source. **Need larger survey!**
GN-z11 was “known” since 2008

same photo-z as with new data, but was ruled out as not likely to lie at $z>9$
due to single band detection and its luminosity (Bouwens+10)
The UV Luminosity Function at the Cosmic Frontier

Slower evolution at the bright end of the UV LF?

→ Need wider area NIR imaging data now to accurately determine number density of bright sources and to find such candidates for JWST follow-up
JWST/NIRSpec: Unprecedented Spectra

Simulation based on z=7.73 source from Oesch+15

- JWST will be extremely efficient in spectroscopic characterization of z>7 galaxies
- For brightest targets, like the recently confirmed target EGS-zs8-1 at z=7.73, we will even be able to measure absorption lines

What is the ionization state of gas in early galaxies?
What is their dynamical state?
Summary

- **Deep imaging with HST** enabled the detection of an unprecedented sample of galaxies at z>3 (11’000), and extended our frontier into the heart of the cosmic reionization epoch (>800 galaxies at z~7-10). Cosmic Frontier: z=11.1

- The **UV LF is extremely steep** during the reionization epoch (faint end slopes as steep as $\alpha = -2$) ➔ ultra-faint galaxies likely main drivers for reionization

- The **cosmic SFRD** evolves **gradually at z~4-8**, then drops **rapidly at z>8** by a factor 10x in only 170 Myr

- Combination of very deep **HST and IRAC** data allow us to measure rest-frame optical colors and **stellar mass build-up** from z~10 to z~3-4. We now explored **97% of cosmic history** in build-up of star-formation and mass

- Discovery of **GN-z11 in current search area is surprising** according to models: **Need larger area surveys** to confirm the number densities of bright galaxies at z>10. Needs to be done **now with HST**, likely won’t be done with JWST!