Galaxies in the first billion years

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Did the first galaxies reionize the Universe?

Want to establish 3 things:

1. Number density of galaxies
   = Luminosity function

2. Number of ionizing photons produced per galaxy
   = stellar populations

3. How many of these photons get out of galaxy to ionize the IGM
   = escape fraction
Our approach:

• No colour cuts – fit all photometry and use redshift probability distribution

• Combine ground-based and HST surveys for maximum dynamic range
High redshift galaxies: 4.5<z<6.5

Stacked data for ~750 5<z<6 LBGs

- $z_{\text{phot}} = 5.43$
- $A_v = 0.0$
- Age = 400 Myr
- Mass = $10^{10.0} \text{M}_\odot$

Photo-zs easy, and accurate, given deep enough multi-band imaging
High redshift galaxies: $4.5<z<6.5$

Combining UDS and HST data-sets provides 5 magnitudes of dynamic range
High redshift galaxies: $4.5 < z < 6.5$

Combining UDS and HST data-sets provides 5 magnitudes of dynamic range

ML fits suggest $M^*$ brightens by $\sim 0.7$ magnitudes from $z=6$ to $z=5$

No significant evolution of normalization or faint-end slope
VLT spectroscopy - zUDS

~50% of luminous LBGs observed at z>6 are strong LAEs

Lyα line fluxes are typically $3 \times 10^{-17}$ cgs (EW$_0 \sim$35 Angstroms), i.e. SFR$\sim 10$ M$_\odot$ yr$^{-1}$

SED analysis (0.35µm-4.5µm) currently on-going - Curtis-Lake et al. (2011)
– see Schenker et al. (2011) & Pentericci et al. (2011) on declining Lyα fraction at $z \sim 7$
$z > 7$ - Wide Field Camera 3 (WFC3)

- Two channel, UVIS and NIR (YJH)
- NIR channel has 4.5 square arcmin FOV
- Image quality of $\sim 0.15''$ FWHM
- Order of magnitude better than NICMOS

$Y \ J \ H = 29(AB)$ imaging allows LBG selection out to $7 < z < 10$

McLure, Dunlop et al (2010)
HST WFC3 Early Release Science Data

Data reduction by A. Koekemoer (STSCI)

45 sq. arcmins in GOODS-S
YJH imaging (2 orbits per filter)
5-sigma depth ~ 27.5 (AB)
WFC3 Imaging of the HUDF: Example SED fits
McLure, Dunlop et al. 2010

ID No. 835 $z_{\text{phot}} = 7.20$
Now using IRAC data in object selection

IRAC deep 3.6 micron imaging deconfused with WFC3 H-band

McLure, Dunlop et al. (2011)
The rapidly evolving LF

Combining UDS and HST data-sets provides 5 magnitudes of dynamic range

M* down by ~0.7 mag from z=5 to z=6 (~250 Myrs)

Now have reasonable constraints on z=7 LF

M* down again by ~0.5 mag from z = 6 to z = 7

see also Bouwens et al. (2011), and Grazian et al. (2011)
Stellar masses and star-formation rates at high-z

Recent observational results suggest sSFR may remain constant ($\sim 2 \text{ Gyr}^{-1}$) all the way from $z=2$ to $z=7$.

Theoretically expect high gas inflow rate at high redshift, and that sSFR should increase as roughly $\sim (1+z)^{2.5}$.

Are these results incompatible?
Stellar masses and star-formation rates at high-z
McLure, Dunlop et al. (2011)

Full photo-z analysis of the z>6 population in the HUDF, HUDF09-2 & ERS fields

Focus on trying to construct the most robust sample of z>6 LBGs possible

Deconfusion analysis employed to include long-wavelength IRAC photometry in selection
Stellar masses and star-formation rates at high-z

Red line shows the z=2 relation from Daddi et al. (2007)

Left: results from SED fits assuming constant SFH, Av=0, 0.2Z\odot

Right: results using plausible range of SFH, Av and metallicity

both give same average <sSFR> ~ 2Gyr\(^{-1}\)
Available ionizing photons

Beta – UV spectral power-law index

Bouwens et al. 2010b, based on Schaerer models
See also Robertson et al. (2010) Nature review, & Finkelstein et al. (2010)
**Beta – UV spectral power-law index**

Dunlop et al. (2011), see also Wilkins et al. (2011)

Beta = -2.1 if confine attention to >8-sigma detections
Beta bias - simple simulations
Dunlop et al. (2011)

Need deeper data to establish beta at faintest luminosities
Future Prospects (near term)

1. Space-based
   • HST CANDELS
   • Spitzer SEDS
   • deeper WFC3 data in HUDF

2. Ground-based
   • VISTA surveys
   • Suprime-cam zY imaging
   • Hyper-Suprime cam
900 sq. arcmin of 2-orbit H, J, + I & V imaging in the SEDS fields
1. GOODS-N
2. GOODS-S
3. Groth Strip
4. COSMOS/UltraVISTA deep strip
5. UKIDSS UDS

150 sq. arcmin of 12-orbit Y,J,H + z, V imaging in the GOODS fields

~20 z > 1.5 Type Ia SN with near-infrared light curves

900 orbits  (PIs: Faber & Ferguson)
HST Multi-cycle treasury proposal - CANDELS

- UDF GO
- Multi-Cycle Treasury
- Combined

Faint End Slope $\alpha$

$\log_{10} \phi_*$ [Mpc$^{-3}$ mag$^{-1}$]
New ground-based near-IR surveys

VISTA telescope: Paranal, Chile

67 mega-pixel camera (1.5 sq. deg)

Survey operations now underway
UltraVISTA – deepest public survey with Vista telescope

- PIs Dunlop, Franx, Le Fevre, Fynbo
- DEEP - 0.73 sq. deg., $Y=26.7$, $J=26.6$, $H=26.1$, $K=25.6$ (1408 hr)
- WIDE – 1.50 sq. deg., $Y=25.3$, $J=25.2$, $H=24.7$, $K=24.2$ (212 hr)
- Narrow-band survey, at 1.185 microns ($z = 8.8$ for Lyman-alpha) (180 hr)
- 1800 hours over 5 years – commenced Jan 2010

First ESO data release
August 2011
UltraVISTA + CANDELS
Building the wedding-cake……
Even deeper WFC3 imaging in HUDF - 128 orbits in Cycle 19
The most distant galaxies – $z > 9$

Bouwens et al. 2010, Nature
$z = 10$ galaxy?

With new WFC3 photometry
Better UV slope measurements

\[ \beta = 4.33 \times (J_{125} - H_{160}) - 2 \]

\[ \log_{10} \zeta_0 \text{ [s}^{-1} \text{ M}_{\odot}^{-1} \text{ yr]} \]

\[ Z = 5 \times 10^{-3} Z_{\odot} \]

\[ \text{Stellar, } f_{esc} = 1 \]

\[ \text{Nebular, } f_{esc} = 0 \]

\[ \text{f}_{esc} \text{ increasing} \]

Young, Metal Poor BC03, \( \beta = -3.1 \)

Older, Metal Rich BC03, \( \beta = -2.3 \)

\[ z = 7.8 \]

J125 Artificially flux boosted by noise

True J125

Added J140 solves flux boosting bias

Y105, J125, J140, H160
Constraining the LF – Reionization?

$\log_{10} \rho_{uv} \text{ [erg s}^{-1} \text{ Hz}^{-1} \text{ Mpc}^{-3}]$

$z \sim 7$ Galaxies Can Maintain Reionization

$\frac{f_{esc}}{2} = 0.1, \log_{10} \zeta_{Q} = 53.5$

Current UDF + CANDELS

$z \sim 7$ Galaxies Cannot Maintain Reionization

$\frac{f_{esc}}{2} = 0.2, \log_{10} \zeta_{Q} = 53.5$

$m_{H} \text{ [AB mag]}$
Establish robust, substantial samples of galaxies at \( z = 7 – 10 \)
- brighter/rarer ones with UltraVISTA
- L* ones with HST CANDELS
- very faint ones from HST ultra deep fields
- better photometric constraints on beta/escape fraction

Study the implications for galaxy formation & reionisation
with Keck+MOSFIRE, VLT+KMOS

Select targets for JWST in 2018
New award of 128 orbits in HST Cycle 19 to Ellis, Dunlop, McLure et al.

Table 1: Summary of HUDF WFC3/IR exposures (orbits) and depths (AB, 5-σ, 0.4″ apertures)

<table>
<thead>
<tr>
<th>Program</th>
<th>$F_{105W}$</th>
<th>$F_{125W}$</th>
<th>$F_{140W}$</th>
<th>$F_{160W}$</th>
<th>($F_{140W} + F_{160W}$)</th>
<th>Total</th>
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<tr>
<td>Final GO:11563</td>
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<td>(38)</td>
<td>94</td>
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<td>30</td>
<td>23</td>
<td>(53)</td>
<td>128</td>
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<tr>
<td>Orbit Totals</td>
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<td>36</td>
<td>30</td>
<td>61</td>
<td>(91)</td>
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<tr>
<td>Final Depth</td>
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<td>29.5</td>
<td>29.5</td>
<td>29.5</td>
<td>29.9</td>
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