Galaxy Build-up in the First 2 Gyrs

Garth Illingworth
Rychard Bouwens

New Zeal - Old Galaxies
Yale 1977 => Rotorua 07
....in Beatrice Tinsley’s footsteps

HST UDF
Galaxy Build-up in the First 2 Gyrs

Galaxy Formation from z~10 to z~4

With Special Thanks to:
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NZ07: Highest Redshift Galaxies

HST: NICMOS + ACS
Opportunities for Exploring the z~4-10 Universe

Extensive HST ACS Data

Large Ground Based IR Detectors - imagers and spectrographs (for Ly$\alpha$ searches)

New NICMOS fields

Spitzer IRAC data
1) Large samples of *i-dropouts* (z~6 galaxies)

2) **Faint** luminosity functions at z~4, 5, 6

3) Luminosity density; SFR from z~4 to z~7-8

4) z~7-8 detections, z~10 limit, z~7-8 masses

Quantitatively characterized UV-bright galaxies at z~4-5-6
0.9 => 1.6 Gyr to <5% of L* <<\( m^* \)

Detect and characterize galaxies at z~7-8 (0.7Gyr)

Set limits (detections?) at z~9-11 (0.5 Gyr)

NZ07: Highest Redshift Galaxies  *GDI*
The luminosity and masses of galaxies build up very rapidly at \( z > 5 \) (e.g., Springel et al 2005)

Mass Function vs time (\( z \)) from Millennium Simulation

Log Number Density

\[
\begin{align*}
\text{Mass} &= z = 0.00 \\
& z = 3.1 \\
& z = 5.7 \\
& z = 10.1
\end{align*}
\]
The luminosity and masses of galaxies build up very rapidly at $z>5$ (e.g., Springel et al 2005)

Mass Function vs time ($z$) from Millennium Simulation

Mass of $\sim L^*$ galaxies
Galaxies at $z \sim 4-10$

The “dropout” technique:
1) Lyman limit break
2) Ly$\alpha$ break at high $z$

Distant galaxy selection by the “dropout” technique: here a ‘$U$-dropout’ 
(Dickinson 1999)
Galaxies at $z \sim 6$

(i-dropouts)

Dropout Redshift Selection Functions

NZ07: High Redshift Galaxies  GDI
Galaxies at $z \sim 6$

*HST data circa 2005*

$z_{850,AB} \sim 27.1$

320 arcmin$^2$

$z_{850,AB} \sim 28.4$ (10σ)

$z_{850,AB} \sim 29.2$ (10σ)

10 arcmin$^2$
Galaxies at $z \sim 6$

23 $z \sim 6$ i-dropouts in 2003

Star Formation at $z \sim 6$: i-dropouts

Now 506 627 $z \sim 6$ i-dropouts in 2006!

Galaxies at $z \sim 6$: The UV Luminosity Function and Luminosity Density from 506 i-dropouts
Galaxies at $z \sim 6$ (i-dropouts)

23 $z \sim 6$ i-dropouts in 2003

Star Formation at $z \sim 6$: i-dropouts.

Now 506 627 $z \sim 6$ i-dropouts in 2006!

$z \sim 6$ galaxies: 21 (bright) i-dropouts from the UDF
$z_{850,AB} \sim 27$ mag

Galaxies at $z \sim 6$: The UV Luminosity Function and Luminosity Density from 506 i-dropouts.
Galaxies at z~6 (i-dropouts)
Galaxies at $z \sim 6$

UV Luminosity Function

Steidel et al 1999 Luminosity Function

$M^* = -20.25$
$\alpha = -1.73$
$\phi^* = 0.00202$

Rest frame magnitude: UV 1350 Å

LF at $z \sim 6$: goes ~3 mag below $L^*$
Galaxies at $z \sim 4$, 5 & 6

($B$, $V$, $i$-dropouts)

Dropout Redshift Selection Functions

NZ07: High Redshift Galaxies  GDI
Galaxies at $z \sim 4, 5, 6$

*HST data circa 2006*

Wide

HDF-N

GOODS

ZF-S

UDF

UDF-Parallels

Deep

$Z_{850,AB} \sim 27.5 \ (10\sigma)$

320 arcmin$^2$

$Z_{850,AB} \sim 29.2 \ (10\sigma)$

10 arcmin$^2$

$Z_{850,AB} \sim 28.4-28.7 \ (10\sigma)$

40 arcmin$^2$
UV Luminosity Function at z~4, 5, 6
(B, V, i-dropouts)

Measurements done over a very large range in $M_{1600}$: -16/18 to -22.5!
Faint-end slope steep & ~constant
$M^*$ is fainter at higher $z$

Rest frame UV 1600 Å

Bouwens, Illingworth, Franx and Ford 2007

4671 z~4 B-dropouts
1416 z~5 V-dropouts
627 z~6 i-dropouts!
Schechter Luminosity Function Parameters: \( \alpha \) vs \( M^* \)

- Shallow
- Faint-end slope \( \alpha \)
- Steep

- Density \( \phi^* \) is \( \sim \) constant
- Faint end slope: \( \alpha \sim -1.7 \)
- \( M^* \) brightens by \( \sim 0.8 \) mag

\( M_*^{1350,AB} \)

Bright \( M^* \) Faint
Comparing UV Luminosity Functions at $z \sim 4, 5, 6$

Significantly deeper than previous work

¡Some differences!
Is the faint end of the LF steep?
Faint end slope has been hard to determine -- HUDF shows it is very steep
Change of $L^*$ with Redshift

Hierarchical Buildup

Progressive buildup of more luminous (massive) galaxies
Luminosity Density & SFR since $z \sim 6$: for $> 0.3L^*$

“Madau” plot

Luminosity Density: Log ergs s$^{-1}$ Hz$^{-1}$ Mpc$^{-3}$

(Star Formation Rate Density - if no extinction)

SFR: $\log_{10} M_\odot$ yr$^{-1}$ Mpc$^{-3}$

Bouwens, Illingworth, Franx and Ford 2007

NEW Determinations

"Madau" plot

Bouwens, Illingworth, Franx and Ford 2007
Star Formation Rate (SFR) History from $z \sim 6$

Star Formation History for $>0.04L^*$

Log SFR: $M_\odot \, yr^{-1} \, Mpc^{-3}$

Dust-corrected SFR shows a more significant drop to high redshift than uncorrected (less extinction at high $z$).
Galaxies at $z \sim 7-8+ \ & z \sim 10$

Dropout Redshift Selection Functions

NZ07: High Redshift Galaxies  \textit{GDI}
Dropouts - Lyman Break Galaxies at $z \sim 7$

Model galaxy at $z = 7.0$

Unattenuated Spectrum

Attenuated Spectrum

No Detection

Blue Continuum
Galaxies Beyond \( z \sim 6 \) are the Frontier

High Redshift Galaxy Candidates: HST, Subaru, VLT, Keck

The \( z > 6 \) universe is exploration territory:
1) find and confirm sources
2) get number density
Searches for $z \sim 7-8+$ Galaxies (*z-dropouts*)

Many fields with deep ACS and NICMOS data for dropout searches

ACS GOODS and UDF (blue)

NICMOS (orange and red) > ~20 arcmin$^2$
Evolution of z ~ 7-8 Galaxies vs z~6


- **Most conservative selection - get 1**
  - Detect 4, but expect 17±4
- **Less conservative selection - get 3 more**
  - Detect 1 but expect 10±4

Inconsistent with no evolution at >99.5%
Changes in UV LF at z~7 vs later times (z~4-6)

Assume similar faint-end slope $\alpha \sim -1.7$

(only 200 Myr earlier at z~7-8 vs z~6)

Progressive buildup of more luminous (massive) galaxies continues to z~7-8
z~10 J-dropout search

Search for J-dropouts in all deep NICMOS J+H data from HDF-N, HDF-S, UDF, and UDF parallels (~800 HST orbits)

HDF-N Thompson
H~28.1 mag, 0.8 arcmin²
HDF-N Dickinson
H~27.0 mag, 5.2 arcmin²
HDF-S Parallel
H~28.2 mag, 0.8 arcmin²

UDF Thompson
H~27.5 mag, 5.8 arcmin²
UDF Parallel #1
H~28.5 mag, 1.3 arcmin²
UDF Parallel #2
H~28.5 mag, 1.3 arcmin²

5σ, AB mags

Galaxies at $z \approx 10$ (J-dropouts)

$J-H>1.8$ “J-dropout” criterion $\Rightarrow 11$ J-dropout candidates in 14.7 arcmin$^2$

8 of the 11 were clearly NOT high redshift objects - detected in optical bands or had quite red $H-K$ colors.

$\Rightarrow 3$ $z \approx 10$ candidates (from 800 HST orbits...!)

Further $\sim 2$ are likely to be contaminants

Example: Low Redshift Contaminant
“Dickinson HDF-N J-dropout”

Log Luminosity Density: 
\[ \text{ergs s}^{-1} \text{ Hz}^{-1} \text{ Mpc}^{-3} \]

Log SFR: 
\[ M_\odot \text{ yr}^{-1} \text{ Mpc}^{-3} \]

“Cosmic Variance” due to large scale structure:
at \( z \sim 4-6 \) \( \sim 14\% \ \text{RMS} \)
at \( z \sim 7-8 \) \( \sim 30\% \ \text{RMS} \)
at \( z \sim 10 \) \( \sim 19\% \ \text{RMS} \)

At \( z \sim 7-8 \) vs \( z \sim 6 \): very substantial drop at bright end (>0.3L*)

Upper limit from \( z \sim 10 \) search

Luminosity Density & SFR History
Star Formation Rate (SFR) History from z~10

Star Formation History for >0.3L*

Log SFR: $M_\odot$ yr$^{-1}$Mpc$^{-3}$

Large drop at z~7-8 for luminous (more massive...) galaxies
-- less if measurements extended fainter??
Spitzer Observations of z~7 Galaxies

NZ07: High Redshift Galaxies  GDI
Spitzer IRAC Observations of z~7 Galaxies
Rest-frame UV and optical fluxes from HST & Spitzer

4 $z$-dropout candidates from the HUDF

From Bouwens, Thompson, et al. 2004 and Bouwens, & Illingworth 2006

SED Fits of $z\sim 7$ Galaxies from HST and Spitzer

Stellar Masses of $0.3 - 1.0 \times 10^{10} \, M_\odot$
Ages of $\sim 50-200$ Myr - SFR $\sim 5-10 \, M_\odot \, yr^{-1}$
Substantial star formation under way at $z\sim 8-10!$

Mass Buildup from $z \sim 7$

Stellar Mass Density vs Redshift

From $z \sim 7$ (0.7 Gyr) to present day

Eyles et al. 2006
Galaxies at $z \sim 4, 5, 6, 7-8+$ & $z \sim 10$

SUMMARY

Dropout Redshift Selection Functions

NZ07: High Redshift Galaxies  GDI
Evolution of the UV Luminosity Function

**Hierarchical Buildup**

**Bright**

- Characteristic UV Luminosity
- $M^*_\text{UV}$

**Faint**

- Downsizing

**Redshift**

$z$
Galaxy Build-up in the First 2 Gyrs (z~10 ⇒ 4)  
Conclusions

Superb ACS and NICMOS data for z~4-10 dropout searches

~4700 B-dropouts (z~4), ~1420 V-dropouts (z~5) and ~620 i-dropouts (z~6)

z~6 UV Luminosity Function rigorously determined to ~3 mags below L*

z~6 galaxies ~consistent with contributing UV flux sufficient to complete reionization

Faint end slope ~constant at α ~ -1.7 for z~4, 5, 6 Luminosity Function

Substantial evolution at the bright end of the UV LF from z~7-8 to z~3
  Characteristic luminosity L*_{UV, z~6} is ~50% fainter than that at z~3.

Luminous z~7 galaxies very rare – substantial decrease in luminosity density to z~7-8 from z~6 for >0.3L* galaxies

Two z~7 galaxies confirmed by Spitzer IRAC measurements

SED Masses for Spitzer objects ~0.3-1 x 10^{10} M_⊙ – ages are ~50-200 Myr

NZ07: High Redshift galaxies  GDI
New Exciting Opportunities for Exploring the $z > 6$ Universe

HST ACS Data

Spitzer IRAC data

New NICMOS fields

Large Ground-Based IR Imagers & Multiple-object Spectrographs

HST SM4 - WFC3 IR

JWST