Evolution of Lyman Break Galaxies from $z=5$ to 3

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Outline

• Lyman Break Galaxies: Introduction
• Survey of LBGs at z~5 (~1 Gyr post Big Bang)
• Results
  • UV Luminosity Function at z~5
  • Clustering
  • Opt. Spectroscopy
  • UV-Optical Colors and Spectral Energy Distribution
• Implications for the Evolution of Star-forming Galaxies in the Early Universe
Lyman Break Galaxies (LBGs)

- A Technique based on Broad-band Photometry (Colors) to Select Galaxies at High-Redshift
  - Pioneered by Steidel et al. (1992-)
- Spectral Break at Rest-Frame <1216A
- High-z (z>3) Star-Forming Galaxies
  - UV Luminous
  - Flat UV Continuum (=Less Dusty)
SED and Filters

Rest-frame Wavelength (angstrom)

$z = 5$

Flux Density ($f\nu$)

V

lc

z'

Images of sources with annotations.
Two-Color Diagram

$z = 4.5$

$E(B-V) = 0$

$E(B-V) = 0.4$
Properties of LBGs at z=3

- **UVLF:** High SF Density
- **Age:** \( \sim 100 \text{ Myr} \)
- **Stellar Mass:** \( \sim 10^{10} \ M_{\text{Sun}} \)
- **Metallicity:** \( \sim \text{Half Solar} \)
- **Clustering:** \( r_0 \sim 4h^{-1}\text{Mpc} \)
- **Descendants:** Corresponds to Today’s Massive Galaxies (through Many Merging Events)?
Properties of LBGs at z~3


Based on HST and VLT Observations
Properties of LBGs at $z \sim 3$

Survey of Lyman Break Galaxies at $z \sim 5$
Optical Observations

- Subaru / Suprime-Cam
  - Very Wide-Field (34’x27’) among ≥8m Telescopes
- V, I, z’ Filters to Sample z=5 LBGs
- Highest-z with Well-Established Optical Filters
- ~1 Gyr Prior to z=3: Change Expected?
- Follow-Up MOS Spectroscopy with Subaru / FOCAS
Two Target Fields

- HDF-N / GOODS-N
- J0053+1234 (One of Caltech Faint Galaxy Redshift Survey Fields)
- Both Fields Contain Plenty of Galaxies with Spectroscopic Redshifts
- Crucial to Defining Color Criteria & Contamination Estimates
- Total Effective Survey Area: 0.36deg$^2$
HDF-N / GOODS-N

~30'

V: 28.2
Ic: 26.9
z': 26.6
(5σ, 1.2'')
J0053+1234

V: 27.8
Ic: 26.4
z’: 26.2

(5σ, 1.2’’)

~30’
Two-Color Diagram

Galaxies Confirmed to be at $z \sim 5$

Galaxies at $z < 4.5$ (Cohen et al. 2000)
UV Luminosity Function
UV Luminosity Function

$z=4$, Sawicki and Thompson (2005)
$z=5$, Iwata et al. (VIz')

$z=3$, Sawicki and Thompson (2005)
$z=5$, Iwata et al. (VIz')
$z=6$, Bouwens et al. (2004)

M*:-20.8~-21.3
$\alpha$: -1.1~1.5
Differential Evolution of UV LF

• From $z=5$ to $z=3$, Number Density of UV Luminous LBGs is Almost Constant, While Number Density of Fainter LBGs Increases.

• UV LF at $z\sim5$ Might be Still Controversial; Some Authors Claim Significant Drop From $z\sim3$ in Luminous Part.

• Change in UVLF Shape from $z=6$ to 5?
  • Related to the End of Cosmic Reionization?
UV LF at $z \sim 4$ to 6

$z=4$, Sawicki and Thompson (2005)

$z=3$, Sawicki and Thompson (2005)

$z=5$, Iwata et al. (VIz')

$z=5$, Ouchi et al. (VI'z')

$z=5$, Ouchi et al. (Ri'z')

$z=6$, Bouwens et al. (2004)
Two-Color Diagram

Galaxies Spectroscopically identified to be at $z \sim 5$

$z = 4.5$

Galaxies at $z \leq 4.5$ (Cohen et al. 2000)
Raw Number Counts are Different

Number Counts w/o Completeness/Contamination Correction are Different; Color Criteria is NOT a Primary Cause of Discrepancy.
Cosmic Star Formation History

\[ M_{UV} < \infty, \text{ Extinction Corrected } E(B-V)=0.15 \]
Clustering: Angular Correlation Function

\[ \omega(\theta) \]

\[ 25.5 < z'(AB) < 26.5 \]
Optical Spectroscopy

- Subaru/FOCAS (MOS mode)
- ~9 Objects Confirmed So Far
- Composite Spectra of UV Luminous LBGs at $z \sim 5$
  - Absense of Strong Ly$\alpha$ Emission
  - Large EW of Low-ionization Interstellar Metal Lines
Lyα Eq. Widths at z~5

Absence of Lyα Emission in UV Luminous LBGs
UV-Optical Colors and SEDs
Stellar Population: $z=3$ LBGs

- Sawicki and Yee (1998); Papovich et al. (2001), Shapley et al. (2001)
- Young: Median Age < 100 Myr
  - “Age” = Onset from Last SF
- Stellar Mass: $\sim 10^{10} \, M_{\odot}$
Stellar Population: $z=3$ LBGs

Papovich et al. 2001

$Z=0.2Z_\odot$, Salpeter IMF

$\bullet$ $z < 2.95$

$\triangle$ $z > 2.95$

Papovich et al. 2001
Rest-frame Opt. Data for $z=5$ LBGs

- K’-Band Imaging with Subaru / CISCO
  - 7 / 8 LBGs with $l_c<25.0$ Detected
- Spitzer / IRAC Public Data from GOODS
  - $\sim100$ LBGs Detected in GOODS DR1
- Biased to Luminous Objects
SEDs and Filters for $z=5$
Examples of IRAC Detections

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UV-Optical SEDs

$z \sim 3$ (Shapley et al.01)

$z \sim 5$ (IRAC, CISCO)
UV-Optical Colors

Shapley et al. 01

This Work, IRAC
Opt-Luminous LBGs are Red

Detected in Multiple IRAC Bands
Single Band Detection

*preliminary*
SED Fitting

- Preliminary Analysis Based on V, Ic, z’ and Spitzer/IRAC Ch1-4
- Constant SFR / Exp-Decay SFH
- IRAC Data: Aperture Photometry with Fixed Correction for Each Channels
SED Fitting: Stellar Mass

Luminous LBGs at z~5 Already Assembled ~10^{10}Msol Stars

*preliminary*
SED Fitting: Stellar Mass

For IRAC Fluxes MAG_AUTO (SExtractor) Used
SED Fitting: Stellar Mass

Exponentially-Decaying SF History Adopted
SED Fitting: Age

SF Age is Hardly Constrained: NIR Imaging Required
SED Fitting: Dust Attenuation

Mostly $E(B-V)<0.5$. Dependence on IRAC Flux in the Case of Constant SFR Models
• UV Luminosity Function:
  • No Significant Change from z=5 to 3 in UV-Bright Part
  • Increase of Number Density in Faint Part with Decreasing Redshift
• UV Luminous LBGs Show Stronger Clustering
• Absense of Ly$\alpha$ Emission and Large EWs of Metal Lines in Luminous LBGs at z$\sim$5
• UV/Optical Luminous LBGs Have Already Assembled $\sim 10^{10} M_{\odot}$ by z$\sim$5
LBGs’ Evolution Depends on Luminosity. Luminous LBGs Evolve Early.

Luminous Objects - Massive DM Halos

Biased Galaxy Formation
SF Starts from Rare Peaks of Matter Density
Down-Sizing in Early Universe?

If we assume UV luminous LBGs are hosted by massive DM halos (← Clustering),

- SF starts early in the rare massive DM halos, and averaged SFR remains high until z~3
- SF in fainter LBGs (i.e., in less massive DM halos) are ignited later, and number density increases from z~5 to z~3
- Note: This scenario is different from “Down-Sizing” in lower-z
Schematic View of the Differential Evolution Scenario

DM Halo Mass

Cosmic SF Density

No UVLF Change in Bright End

Increase of Faint Galaxies

Absence of Massive Galaxies with High SFR

= Star Formation Rate

Cosmic Age
Next Steps

- UV LF at z~5:
  - Bright Part: Optical Spectroscopy
  - Faint Part: Deeper Imaging Survey
- SEDs at z~5:
  - Spitzer / IRAC Obs. for “Flanking Fields” of GOODS-N in Cycle2
  - Deep Near-IR Imaging