High Redshift Galaxies in CLASH

Marc Postman
Space Telescope Science Institute
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Rychard Bouwens, Larry Bradley, Dan Coe, Claudio Grillo, Polo Infante, Dan Kelson, Anton Koekemoer, Leonidas Moustakas, Piero Rosati, Renske Smit, Wei Zheng, Adi Zitrin & the entire CLASH team
An HST Multi-Cycle Treasury Program designed to place new constraints on the fundamental components of the cosmos: dark matter, dark energy, and baryons.

To accomplish this, we are using galaxy clusters as cosmic lenses to probe dark matter and magnify distant galaxies.
Key Questions in the Era of Extremely Large Telescopes

- When was the epoch of first galaxy formation?
- What are the characteristics (mass, “metal” abundance, star formation rates, global structure) of the most distant galaxies in the universe ($t_U < 800$ Myr)?
- What was their role in ionizing the intergalactic medium?
- How do galaxies build up and evolve at the earliest times?
The Impact of Lensing Clusters

Hubble Probes the Early Universe

1990
Ground-based observatories

1995
Hubble Deep Field

2004
Ultra Deep Field

2010
UDF WFC3 IR

FUTURE
JWST, ALMA & ELT’s

Redshift (z):
Time after the Big Bang

HST Frontier Fields

CLASH
A2218
A1689

z~7.6
z~11
?

1 6 billion years
4 1.5 billion years
5 800 million years
6 480 million years
10 200 million years
>20

Ground-based observatories
Hubble Deep Field
Ultra Deep Field
UDF WFC3 IR
JWST, ALMA & ELT’s

1990
1995
2004
2010

z~11
Comprehensive Multi-wavelength Coverage

- HST 524 orbits: 25 clusters, each imaged in 16 passbands. (0.23 – 1.6 µm) 20 orbits per cluster (~27 ABmag @ 5σ)
- CLASH observations are 95% done - 23 clusters completed, rest done by July 6.
- Subaru wide-field imaging (0.4 – 0.9 µm)
- Spitzer Space Telescope archival and new cycle 8 data (3.6, 4.5 µm)
- Chandra x-ray Observatory archival data (0.5 – 7 keV)
- SZE observations (Bolocam, Mustang) to augment existing data (sub-mm)
- VLT, LBT, Magellan, MMT, Palomar Spectroscopy
CLASH Gallery: First 20 Clusters

A383 (0.187)  A209 (0.206)  A2261 (0.224)  RXJ2129 (0.234)  A611 (0.288)

MS2157 (0.313)  RXJ1532 (0.345)  RXJ12248 (0.348)  MACS1115 (0.352)  MACS1931 (0.352)

MACS1720 (0.391)  MACS0416 (0.42)  MACS1206 (0.440)  MACS0329 (0.450)  RXJ1347 (0.451)

MACS1149 (0.544)  MACS0717 (0.548)  MACS2129 (0.570)  MACS0647 (0.584)  MACS0744 (0.686)
The Power of WFC3-IR Camera

CL J1226+3332 (z=0.89)

Sum of all current ACS data

Sum of all current WFC3-IR data

Cluster is x-ray luminous and known to be a good lensing system but no giant arcs.

Oh snap! There is a giant arc. photo-z ~ 1.95
The Power of WFC3-IR Camera

CL J1226+3332 (z=0.89)

Sum of all current WFC3-IR data

Oh snap! There is a giant arc. photo-z ~ 1.95
Richard et al. 2011: $z = 6$ lensed Galaxy in A383

$z = 6.027$ Galaxy

$11.4 \times$ magnification

Abell 383

$z = 6.027$ Galaxy

$\sim 800$ Myr

$z_{\text{FORM}} \sim 25$
MACS J0329-02: Quadruply-lensed Galaxy at $z_{ph} = 6.15$

Magnifications: #1 = 11.6, #2 = 17.6, #3 = 3.9, #4 = 3.7

Zitrin et al. 2012

De-lensed view (source plane)

HST PSF

90 pc/pixel

0.2"

Age <400 Myr  $z_F < 9.8$
Some Examples of CLASH $z > 6$ Candidates
CLASH: Sample High-z Candidate

24.6 AB

z~5.6

Lyman-α @8151 Å

z = 5.703

VLT – VIMOS (1 hour exp)
P. Rosati et al.
Lensing wins at brighter magnitudes / higher redshifts

Bouwens12a luminosity function evolving all 3 parameters
CLASH: Magnified High-z Galaxies

CLASH finds a large number of high-redshift galaxies

- Steep LFs largely mitigate the decreased intrinsic source-plane area
- Higher spectral and spatial resolution than typical LBG surveys
- Detection of sources fainter than possible in most high-z surveys

<table>
<thead>
<tr>
<th></th>
<th>z ~ 6</th>
<th>z ~ 7</th>
<th>z ~ 8</th>
<th>z ~ 9</th>
<th>z ~ 10</th>
<th>z ~ 11</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 clusters</td>
<td>192</td>
<td>43</td>
<td>12</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>251</td>
</tr>
<tr>
<td>Survey extrapolation</td>
<td>~300</td>
<td>~67</td>
<td>~19</td>
<td>~3</td>
<td>~2</td>
<td>~2</td>
<td>393</td>
</tr>
</tbody>
</table>

Largest sample of lensed star-forming galaxies at z >~ 5.5 to date

7 multiply-imaged systems at z >~ 5.5

Bradley et al. (2013a)
Median magnifications: $\mu \sim 4.7, 4.7, 4.9$ for $z \sim 6, 7, 8$ samples

Intrinsic (unlensed) magnitudes nearly reach 34 mag

Caveat: largest magnifications have large uncertainties!
Two $z > 9$ Lensed Galaxies

$z = 9.6$ object in MACSJ1149+2223

$z = 10.8$ object in MACSJ0647+7015


z > 9 Lensed Galaxy Candidates

MACS1149-JD1 (z = 9.6)

Neither object’s position and flux varies significantly over course of 2 – 3 months

MACS0647-JD1 (z = 10.8)
Spectral Energy Distributions

MACS1149-JD: $z = 9.6 \pm 0.2$
Stellar mass: $\sim 1.5 \times 10^8$ M$_{\odot}$
SFR: $\sim 1.2$ M$_{\odot}$/yr
Age: $< 200$ Myr (95% CL), $z_{\text{Form}} < 14.2$
$r_{1/2}^2$: $\sim 0.14$ kpc (de-lensed)

MACS0647-JD: $z = 10.8 \pm 0.5$
Stellar mass: $10^8 - 10^9$ M$_{\odot}$
SFR: $\sim 4$ M$_{\odot}$/yr (Salpeter IMF)
Age: $< 400$ Myr (95% CL)
$r_{1/2}^2$: $< 0.10$ kpc (de-lensed)

In both cases, best fit SED is a starburst galaxy

Plus symbols represent new, deeper IRAC data

Green triangle = 1 sigma upper limit
Red square = predicted model flux
Yellow triangle = non-detection with 2 sigma errors shown
Observed positions and fluxes are consistent with our lens models. Models are based on 20 strongly lensed images of 8 other galaxies.
Previous searches for galaxies in the first 500 Myr came up short. Only one candidate was found where six were expected. This suggested a dramatic buildup in galaxy numbers.
Such dramatic evolution has implications (e.g., Trenti+2010, Jaacks+2011, Alvarez+2012, Bouwens+2012, Dunlop+2012/13, Robertson+2013)

- low mass (<10^9) galaxies must be a dominant source of the ionizing radiation at z > 8
- sources of cosmic re-ionizing radiation at z>8 may have low clumping factors
- sources may have harder UV energy output (higher beta) and/or higher escape fractions
- Not enough faint galaxies to reionize the z>8 universe? Other more exotic ionizing energy mechanisms may need to be invoked.
CLASH discoveries are consistent with expectations but errors cannot rule out dramatic evolution seen in UDF

adapted from Coe et al. 2013
CLASH and UDF12 yield 4–8 candidates at $z > 9$ where previously only one was known.

Highest spectroscopic redshift: $z = 7.215$ (Shibuya12)
CLASH and UDF12 provide our first constraints on $z > 9$ galaxy evolution. Additional observations are required.
Deeper and wider NIR lensing surveys required

\[ M_{UV} \sim 10 \] (smallest galaxies?)

other uncertainties:
- escape fraction
- clumping factor

Galaxy Number Density

Log Galaxies / mag / \Delta z / arcmin

Observed F160W AB Magnitude

\( z \sim 8 \) luminosity function data (Bradley12)
Rest-Frame UV-Continuum Slopes ($\beta$)

$\beta$ is the power-law slope of the UV continuum: $f_\lambda \sim \lambda^\beta$

CLASH: IR spectral coverage gives better measures at $z \sim 6-8$

Find $\beta$s that are bluer than typical local starbursts ($\beta < -2.0$)

$z \sim 6$: $\langle \beta \rangle = -2.18 \pm 0.05$

$z \sim 7$: $\langle \beta \rangle = -2.45 \pm 0.21$

$z \sim 8$: $\langle \beta \rangle = -2.36 \pm 0.30$

$\Rightarrow$ $\beta$ becomes bluer at fainter intrinsic magnitudes

Consistent with little or no dust

Bradley et al. (2013b)
Summary: CLASH High-z Galaxies

- CLASH identifies 251 high-redshift (z ≥ 5.5) galaxies (in 16 clusters). Expect ~400 in full survey (25 clusters).
  - Similar observed surface densities as legacy field surveys down to $H_{160}$ ~ 27.5 AB (5σ limit).
- CLASH has at least two robust z > 9 lensed galaxy candidates with 8x – 15x magnification that yield H-mag 25.7 – 25.9.
- CLASH + IR-UDF provide the first results on the star formation rate density at z > 8 (albeit with large uncertainties).
  - Searches for z > 8 galaxies may suggest dramatic evolution in SFRD
  - The Frontier Fields program should provide much better constraints.
- Lensing provides most detailed look at structure of z > 6 galaxies. Often reach 100 – 200 pc resolution at these redshifts – equiv. to resolution of diffraction limited 10-m to 20-m telescope.
- Find β’s that are bluer than typical local starbursts: $<\beta> = -2.18, -2.45, -2.36$ for z~6, 7, 8, respectively.

HST + ELTs + JWST + ALMA + space NIR sky surveys have and/or will transform our understanding of the early universe.