**J/ApJ/792/76** Lensed z~6-8 galaxies behind CLASH clusters (Bradley+, 2014)

CLASH: a census of magnified star-forming galaxies at z ~ 6-8.

Bradley L.D., Zitrin A., Coe D., Bouwens R., Postman M., Balestra I., Grillo C., Monna A., Rosati P., Seitz S., Host O., Lemze D., Moustakas J., Moustakas L.A., Shu X., Zheng W., Broadhurst T., Carrasco M., Jouvel S., Koekemoer A., Medezinski E., Meneghetti M., Nonino M., Smit R., Umetsu K., Bartelmann M., Benitez N., Donahue M., Ford H., Infante L., Jimenez-Teja Y., Kelson D., Lahav O., Maoz D., Melchior P., Merten J., Molino A.

<Astrophys. J., 792, 76 (2014)>
=2014ApJ...792...76B (SIMBAD/NED BibCode)

**ADC_Keywords**: Clusters, galaxy ; Gravitational lensing ; Galaxies, photometry ; Photometry, HST ; Redshifts
**Keywords**: galaxies: evolution - galaxies: high-redshift - gravitational lensing: strong

**Abstract**:
We utilize 16 band Hubble Space Telescope (HST) observations of 18 lensing clusters obtained as part of the Cluster Lensing And Supernova survey with Hubble (CLASH) Multi-Cycle Treasury program to search for z ~ 6-8 galaxies. We report the discovery of 204, 45, and 13 Lyman-break galaxy candidates at z ~ 6, z ~ 7, and z ~ 8, respectively, identified from purely photometric redshift selections. This large sample, representing nearly an order of magnitude increase in the number of magnified star-forming galaxies at z ~ 6-8 presented to date, is unique in that we have observations in four WFC3/UVIS UV, seven ACS/WFC optical, and all five WFC3/IR broadband filters, which enable very accurate photometric redshift selections. We construct detailed lensing models for 17 of the 18 clusters to estimate object magnifications and to identify two new multiply lensed z ≳ 6 candidates. The median magnifications over the 17 clusters are 4, 4, and 5 for the z ~ 6, z ~ 7, and z ~ 8 samples, respectively, over an average area of 4.5 $arcmin^2$ per cluster. We compare our observed number counts with expectations based on convolving "blank" field UV luminosity functions through our cluster lens models and find rough agreement down to ~27 mag, where we begin to suffer significant incompleteness. In all three redshift bins, we find a higher number density at brighter observed magnitudes than the field predictions, empirically demonstrating for the first time the enhanced efficiency of lensing clusters over field surveys. Our number counts also are in general agreement with the lensed expectations from the cluster models, especially at z ~ 6, where we have the best statistics.

**Description**:
CLASH is a 524 orbit multi-cycle treasury program to observe 25 galaxy clusters to a total depth of 20 orbits each, incorporating archival HST data for our cluster sample whenever possible (Postman et al. 2012, J/ApJS/199/25). Each cluster is observed using WFC3/UVIS, ACS/WFC, and WFC3/IR to obtain imaging in 16 broadband filters spanning from 0.2 to 1.7 um (for the throughput curves of each filter, see Postman et al. 2012, J/ApJS/199/25 or Jouvel et al. 2014, J/A+A/562/A86). We used SExtractor version 2.5.0 (Bertin & Arnouts 1996A&AS..117..393B) in dual-image mode to perform object detection and photometry. For each of our 18 clusters, we constructed a detection image by performing an inverse-variance weighted sum of the images in all five WFC3/IR bands: Y105, J110, J125, JH140, and H160. The local background was measured within a rectangular annulus (default width 24 pixels) and sources were required to be detected at >1σ significance over a minimum area of nine contiguous pixels.

**File Summary**:

| FileName | Lrecl | Records | Explanations |
|---|---|---|---|
| ReadMe | 80 | . | This file |
| table1.dat | 93 | 18 | Observational Details for the Cluster Sample |
| table4.dat | 133 | 196 | Lensed z~6 Candidates Identified Behind 17 CLASH Clusters |
| table5.dat | 133 | 43 | Lensed z~7 Candidates Identified Behind 17 CLASH Clusters |
| table6.dat | 133 | 12 | Lensed z~8 Candidates Identified Behind 17 CLASH Clusters |
| table7.dat | 133 | 21 | Lensed Candidates Identified Behind RXJ1532.9+3021 |

**See also**:
J/ApJS/199/25 : CLASH sources for MACS1149.6+2223 (Postman+, 2012)
J/A+A/562/A86 : CLASH. Photometric + photo-z catalog (Jouvel+, 2014)
J/ApJ/801/44 : HST lensing analysis of the CLASH sample (Zitrin+, 2015)

**Byte-by-byte Description of file**: table1.dat

```
  Bytes Format Units   Label       Explanations
--------------------------------------------------------------------------------
   1- 16  A16    ---     Cluster     Cluster Name
  18- 22  A5     ---     n_Cluster   Notes on Cluster (1)
  24- 31  A8     ---     Alias       Shortened cluster names used in the paper
  33- 34  I2     h       RAh         Rigth ascension (J2000) (2)
  36- 37  I2     min     RAm         Rigth ascension (J2000) (2)
  39- 43  F5.2   s       RAs         Rigth ascension (J2000) (2)
      44  A1     ---     n_RAs       [g] Note on position (3)
      46  A1     ---     DE-         Declination sign (J2000) (2)
  47- 48  I2     deg     DEd         Declination (J2000) (2)
  50- 51  I2     arcmin  DEm         Declination (J2000) (2)
  53- 56  F4.1   arcsec  DEs         Declination (J2000) (2)
      57  A1     ---     n_DEs       [g] Note on position (3)
  59- 63  F5.3   ---     z           Cluster redshift
  65- 69  F5.3   mag     E(B-V)      Reddening
  71- 81  A11    "date"  Start.Date  Observation starting date
  83- 93  A11    "date"  End.Date    Observation ending date
--------------------------------------------------------------------------------
```

**Note (1)**: Notes as follows:
```
    c = Ebeling et al. (2007ApJ...661L..33E)
    d = High-magnification cluster
    e = Hubble Frontier Fields (HFF) cluster
    f = Ebeling et al. (2010MNRAS.407...83E)
    h = Mann & Ebeling (2012MNRAS.420.2120M)
```
**Note (2)**: Cluster coordinates derived from X-ray data, except where noted.

**Note (3)**: g when cluster coordinates derived from optical data.

--------------------------------------------------------------------------------

**Byte-by-byte Description of file:** table4.dat table5.dat table6.dat table7.dat

```
  Bytes Format Units   Label     Explanations
--------------------------------------------------------------------------------
   1- 13  A13    ---     ID        Object identifier (1)
  14- 18  A5     ---     f_ID      Flag on ID (2)
  20- 30  F11.7  deg     RAdeg     Right Ascension in decimal degrees (J2000)
  32- 42  F11.7  deg     DEdeg     Declination in decimal degrees (J2000)
      44  A1     ---   l_I814mag   Limit flag on I814mag
  45- 48  F4.1   mag     I814mag   The HST I band AB magnitude; 0.814 microns
  50- 53  F4.2   mag   e_I814mag   ? Uncertainty in I814mag
      55  A1     ---   l_z850mag   Limit flag on z850mag
  56- 59  F4.1   mag     z850mag   The HST z band AB magnitude; 0.850 microns
  61- 64  F4.2   mag   e_z850mag   ? Uncertainty in z850mag
  66- 69  F4.1   mag     Y105mag   ? The HST Y band AB magnitude; 1.05 microns
  71- 74  F4.2   mag   e_Y105mag   ? Uncertainty in Y105mag
  76- 79  F4.1   mag     Y110mag   ? The HST Y band AB magnitude; 1.10 microns
  81- 84  F4.2   mag   e_Y110mag   ? Uncertainty in Y110mag
  86- 89  F4.1   mag     J125mag   ? The HST J band AB magnitude 1.25 microns
  91- 94  F4.2   mag   e_J125mag   ? Uncertainty in J125mag
  96- 99  F4.1   mag     J140mag   ? The HST J band AB magnitude; 1.40 microns
 101-104  F4.2   mag   e_J140mag   ? Uncertainty in J140mag
 106-109  F4.1   mag     H160mag   The HST H band AB magnitude; 1.60 microns
 111-114  F4.2   mag   e_H160mag   Uncertainty in H160mag
 116-118  F3.1   ---     zphot     Photometric redshift (3)
 120-122  F3.1   ---     E_zphot   Upper limit uncertainty in zphot
 124-126  F3.1   ---     e_zphot   Lower limit uncertainty in zphot
     128  A1     ---     l_mu      Limit flag on mu
 129-133  F5.1   ---     mu        Magnification (4)
--------------------------------------------------------------------------------
```

**Note (1)**: Object identified as Alias-NNNN.

**Note (2)**: Flag as follows:

c = Unresolved object with FWHM<0.22 arcsec in the image plane. There is a small chance that brighter unresolved candidates could be low-mass stars even though we explored such possibilities (see Section 5.3).

d = Using LePhare, we find that these unresolved candidates have a good fit with stellar templates, with $\chi^2_{star}$ comparable or less than $\chi^2_{galaxy}$.

e = While BPZ prefers a high-redshift solution, we note that LePhare slightly prefers a low-redshift solution (z~1) over the high-redshift solution for these three galaxies. Given this and the possible fit with stellar templates, these candidates should be considered less confident than the others.

f = Spectroscopically confirmed multiply-imaged galaxy at z=6.027 Richard et al. (2011MNRAS.414L..31R).

g = Quadruply lensed galaxy at z~6.2 (Zitrin et al. 2012ApJ...747L...9Z).

h = Zitrin et al. (2013ApJ...762L..30Z) report that MACS0419-0419 is part of a visually-identified double system at $z_{phot}$~6.1. The second candidate (at RA=04:16:09.946, DE=-24:03:45.31) fell below our S/N threshold and thus does not appear in this catalog.

i = MACS1115-0352 and MACS1720-1114 have very blue SEDs. While our best-fit photometric redshifts suggest that these are high-redshift

```
      candidates, a possible alternative solution is that they could be
      low-redshift extreme emission-line galaxies with rest-frame equivalent
      widths of ~2000 Angstroms (Huang et al. in prep).
  j = Quadruply lensed galaxy at zphot~5.6 (zspec=5.701)
      (Zitrin et al. 2012, J/ApJ/749/97).
  k = VLT/VIMOS spectroscopy confirms this galaxy at z=5.701 (see Section 5).
  l = Monna et al. (2014MNRAS.438.1417M) found that these two candidates,
      along with three others, are part of a quintuply-lensed system with
      zphot~5.9. Based on their lens model, the magnifications for
      RXCJ2248-0401 and RXCJ2248-1291 (ID4 and ID3, respectively in
      Monna et al. (2014MNRAS.438.1417M) are 2.4 ± 0.2 and 6.0 ± 1.5,
      respectively.
  m = In the recent Hubble Frontier Fields data, this candiate is detected in
      the ultradeep optical data and therefore it is very unlikely to be a
      high-redshift galaxy.
  n = MACS0717-0859 and MACS0717-1730 are spectroscopically confirmed at
      z=6.387 (Vanzella et al. 2014ApJ...783L..12V).
  o = Despite having a best-fit photometric redshift of zphot = 7.2, we suspect
      this unresolved object is most likely a star. Based on our current
      understanding of the z~7 LF (e.g., Bouwens et al. 2011ApJ...737...90B),
      the probability of detecting a slightly-magnified z~7 galaxy with
      H160=23.6 in the small area covered by the clusters in this paper is
      exceedingly small. We list this candidate for completeness, but do not
      use it for subsequent analysis given its suspect nature.
  p = The lens models suggest that this is likely a multiple system at z~6.5.
  q = The lens models suggest that this is likely a multiple system at z~6.6.
  r = In the recent Hubble Frontier Fields data, this candidate is detected in
      the ultradeep optical data and therefore it is very unlikely to be a
      high-redshift galaxy.
Note (3): Photometric redshift estimate with 2σ (95%) confidence
  intervals (see Section 4).  Objects with large lower bounds have a secondary
  peak at lower redshift (z~1-2) that contains at least 5% of the posterior
  probabilty.
Note (4): Magnification estimate from the lens models (see Section 6). Because
  of uncertainties in the precise location of the critical curves, objects with
  magnifications >100 are simply quoted as such. Objects outside the region
  constrained by the strong lensing models have been assigned a magnification
  of 1.1.
```

---

**History:**
    From electronic version of the journal

---

**(End)**          Prepared by [AAS], Tiphaine Pouvreau [CDS]          06-Apr-2017