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The First Half Billion Years ($z > 9$): Results from the Frontier Fields

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Abstract. We present $z > 9$ candidates identified in *Hubble* Frontier Fields imaging of the first four clusters and blank parallel fields (two-thirds of the complete program). Based on the deeper *Hubble* imaging, we revise the redshift estimate of the CLASH $z \sim 9.6$ candidate MACS1149-JD to $z = 9.2^{+0.2}_{-0.5}$ (95% C.L.). We identify a new possible fainter $z \sim 9$ companion $3''$ away (∼1 kpc in the source plane). And we discover a new $z \sim 9.2$ candidate in the MACS1149 parallel field. Combined with previously published candidates at $z \sim 9.8$ and 9.1 (in A2744 and its parallel field, respectively), these five $z > 9$ candidates fall below our published expectation of 8 – 47 at this stage in the program. We attribute some of this shortfall to incompleteness, which we have yet to quantify. At $z \sim 8$ (7.5 – 8.5), we detect 26 candidates down to F160W $H < 28.7$ AB, roughly one-third the ∼82 we expect. If our $z > 9$ incompleteness is similar (∼68%), our results would support the sharp drop in $z > 9$ number counts claimed by some (but not all) previous works and supported by several (but not all) theoretical models. Properly quantifying our incompleteness will require adding simulated high-redshift galaxies into the images and testing our recovery rate. Additionally, incorporating the deep *Spitzer* imaging into our analysis could potentially significantly improve our identification of $z > 9$ candidates by rejecting low-redshift ($z \sim 2$) interlopers. Data from the full Frontier Fields program will provide strong evidence for or against accelerated evolution and a sharp drop in the cosmic star formation rate density at $z > 9$.

Keywords. early universe, galaxies: high-redshift, gravitational lensing

1. Introduction

The *Hubble* and *Spitzer Space Telescopes* with the Wide Field Camera 3 infrared channel (WFC3/IR) and Infrared Array Camera (IRAC), respectively, have revealed over 1,000 candidate $z > 6$ galaxies observed during the first billion years (e.g., Bouwens *et al.* 2015, Finkelstein *et al.* 2015). Such photometric redshifts and color-color selections have been confirmed spectroscopically out to $z = 8.68$ (Zitrin *et al.* 2015).

Very few (∼18) of these high-redshift candidates date back to the first half billion years or so ($z > 9$; < 540 Myr). These $z > 9$ candidates were discovered in the UDF (Ellis *et al.* 2013, Oesch *et al.* 2013); CANDELS (Oesch *et al.* 2014, Bouwens *et al.* 2015); CLASH (Zheng *et al.* 2012, Coe *et al.* 2013); and the Frontier Fields (Zitrin *et al.* 2014, McLeod *et al.* 2015).

The small number of $z > 9$ candidates has led some authors (e.g., Bouwens *et al.* 2011, Oesch *et al.* 2013) to claim a $z > 9$ deficit relative to extrapolations from the luminosity function evolution observed at $4 < z < 8$. This would suggest accelerated evolution and a rapid buildup in the cosmic star formation rate density in the first half billion years. This is supported by several theoretical models (e.g., Mason *et al.* 2015). However, other authors have found the data consistent with more gradual evolution (e.g., Ellis *et al.* 2013, McLeod *et al.* 2015) as predicted by other models (e.g., Behroozi *et al.* 2013).

Table 1. $z > 9$ candidates detected in *Hubble* Frontier Fields imaging (in addition to the triply-lensed $z \sim 9.8$ candidate presented in Zitrin *et al.* 2015).

ID[a]	R.A. (J2000)	Decl. (J2000)	z_b[b]	$P(z > 4)$[c]	F160W (nJy)[d]	magnification[e]	original reference
FFB1-5364-3024[f]	00:13:53.64	−30:23:02.4	$9.1\left[{}^{9.6}_{8.4}\right]$	0.99	14 ± 2		McLeod *et al.* 2015
FFC4-3358-4457[g]	11:49:33.58	+22:24:45.7	$9.2\left[{}^{9.4}_{8.7}\right]$	1.00	196 ± 7	$9.0\left[{}^{19}_{6.0}\right]\left[{}^{11}_{5.1}\right]$	Zheng *et al.* 2012
FFC4-3372-4482 [h]	11:49:33.72	+22:24:48.2	$2.0\left[{}^{8.9}_{1.4}\right]$	0.11	14 ± 2	$8.8\left[{}^{24}_{5.8}\right]\left[{}^{10}_{3.4}\right]$	this work
FFB4-3994-7366	11:49:39.94	+22:17:36.6	$9.2\left[{}^{9.6}_{8.7}\right]$	1.00	29 ± 2		this work

Notes:
[a] ID names encode field and position as in Coe *et al.* (2015).
[b] Bayesian photometric redshift [95% C.L.].
[c] Estimated Bayesian probability of being at high redshift ($z > 4$).
[d] Measured fluxes are given in nJy. AB magnitudes are given by $m_{AB} = 31.4 - 2.5\log_{10}(F_{\rm nJy})$.
[e] Magnification estimates based on submitted models (versions 1-2). We quote the median and 68.3% range of parametric models in brackets followed by the 68.3% range of all models in brackets.
[f] HFF1P-9-2 from McLeod *et al.* (2015): bimodal with best $z \sim 8.9$.
[g] MACS1149-JD from Zheng *et al.* (2012): $z \sim 9.6$. [h] Candidate companion 3″ from MACS1149-JD.

The Frontier Fields (PI Lotz) directors' discretionary program is obtaining deep *Hubble* and *Spitzer Space Telescope* imaging of six massive strong lensing clusters and "blank" parallel fields ∼6′ away. In Coe *et al.* (2015), we estimated that the complete program would yield between ∼12–70 $z > 9$ galaxies brighter than F160W $H < 28.7$ AB. That is, between one and six $z > 9$ galaxies per field depending on the luminosity function evolution at $z > 9$. We showed that these estimates are robust to lens model uncertainties; the lens models submitted by various teams all yield similar estimates in total high-redshift number counts. These expected numbers do not account for incompleteness. (see e.g., Zitrin *et al.* 2014, Oesch *et al.* 2015, Atek *et al.* 2015).

The Frontier Fields program is now two-thirds complete. Four clusters and their associated parallel fields have been observed to full depth with both *Hubble* and *Spitzer*: Abell 2744, MACSJ0416.1-2403, MACS0717.5+3745, MACSJ1149.5+2223. Here we present the first $z > 9$ search to include all of these fields.

2. Analysis

We analyzed the publicly available *Hubble* Frontier Fields image reductions produced by the team at STScI led by Anton Koekemoer. Specifically, we analyzed the v1.0 mosaics with 0.06″/pixel resolution, ACS "self-calibration" (`*selfcal*`), and WFC3/IR time-variable sky correction (`*bkgdcor*`). These image mosaics include *HST* data from previous programs, including CLASH, for the seven Frontier Fields filters. CLASH images are available in 16 filters, so we retrieved the shallower data in these 9 additional filters from the publicly available *Hubble* CLASH images (rebinning the 0.03″/pixel images to 0.06″/pixel). We have not analyzed the deep UV imaging obtained by PI Siana. And most critically, we have not analyzed the deep Spitzer imaging.

For each cluster, we used SExtractor v2.8.6 to detect objects in the weighted stacked WFC3/IR image with the parameters optimized for the CLASH survey (Coe *et al.* 2013). These parameters are not ideal for the deeper Frontier Fields imaging with higher contrasts between bright and faint objects. We began experimenting with more aggressive background subtractions but have not yet found this to yield reliable high-redshift results.

Using these object detections and their defined isophotal apertures, we then ran SExtractor in dual-image mode to obtain photometry in each *HST* filter. We ran BPZ (Bayesian Photometric Redshifts; Benitez *et al.* 2000, Coe *et al.* 2006) to identify high-redshift candidates. We used the original HDFN prior (Benítez *et al.* 2000) which regards

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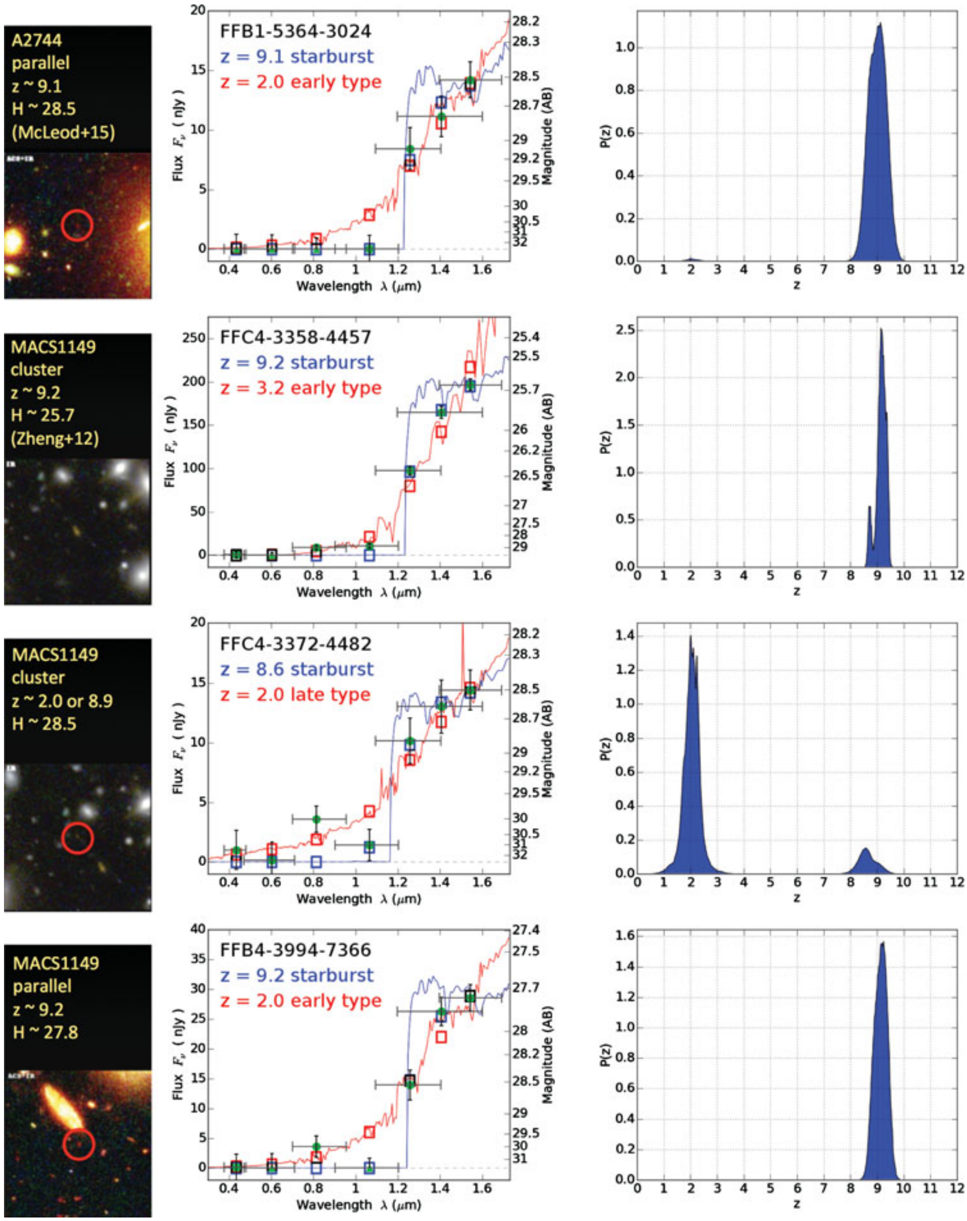

Figure 1. Color images (left), SED plots (center), and $P(z)$ Bayesian redshift probability plots (right) for the $z > 9$ candidates, including FFC4-3372-4482, the possible nearby companion to MACS1149-JD, but not including the triply-imaged $z \sim 9.8$ candidate (see Zitrin *et al.* 2014). Original discovery references are given in parentheses on the left for the first two candidates. Each SED plot shows both the best fit high-redshift ($z > 4$) and low redshift ($z < 4$) solutions. Noisier CLASH *HST* photometry was also used in the analysis but is not shown for clarity.

a $z \sim 10$ starburst to be roughly as likely as a $z \sim 2$ early type. (The prior used by Coe *et al.* (2013) to discover the CLASH $z \sim 11$ candidate was ~100 times more conservative against the high-redshift solution. Bouwens *et al.* (2014) showed this was too conservative based on data from recent surveys.) Finally, we visually inspected the candidates to discard obvious artifacts identified along the edges of the image mosaics.

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3. Results

Table 1 summarizes the $z > 9$ candidates, and Figure 1 shows their color images, SED plots, and Bayesian redshift probability plots $P(z)$. FFB1-5364-3024 was discovered by McLeod *et al.* (2015) as their HFF1P-9-2 in the A2744 parallel field. They found a bimodal $P(z)$ with $z \sim 8.9$ more likely than $z \sim 2$. We find $z \sim 9.1$ to be far more likely than $z \sim 2$. We also recover other $z \sim 9$ candidates reported by McLeod *et al.* (2015) and Ishigaki *et al.* (2015), but our redshift estimates are slightly lower than $z \sim 9$. Probabilistically, a few of these are likely at $z > 9$.

MACS1149-JD at $z = 9.6 \pm 0.2$ (68% C.L.) was discovered previously in CLASH imaging (Zheng *et al.* 2012; see also Bradac *et al.* 2014). Based on the deeper Frontier Fields *HST* imaging, we report an updated redshift estimate of $z = 9.2^{+0.2}_{-0.5}$ (95% C.L.). Nearby ($3''$ away, or ~1 kpc in the source plane), we identify a possible new fainter $z \sim 9$ companion (with a formally more likely redshift $z \sim 2$). And $7.3'$ away in the MACS1149 parallel field, we discover a new $z \sim 9.2$ candidate.

Our nominal pipeline does not detect the triply-imaged $z \sim 9.8$ candidate lensed by Abell 2744 (Zitrin *et al.* 2015). Our more aggressive SExtractor detection does recover the brightest image JD1A, and BPZ gives a $z \sim 9.5$ possibility but deems a $z \sim 2.3$ early type more likely. By including the *Spitzer* photometry (along with that from *Hubble*), Zitrin *et al.* (2015) report that BPZ finds $z \sim 9.7$ to be far more likely than $z \sim 2$.

All together, the five $z > 9$ candidates fall below our published expectation of $8 - 47$, that is ~47 for smooth evolution and ~8 for accelerated evolution. We attribute some of this shortfall to incompleteness, which we have yet to quantify. Unless we are missing ~90% of the $z > 9$ candidates, this would seem to support rapid evolution in the $z > 9$ luminosity function. We note that at $z \sim 8$ $(7.5 - 8.5)$, we detect 26 candidates down to F160W $H < 28.7$ AB, roughly one-third the ~82 we expect. We may expect our $z > 9$ incompleteness to be similar (~68%). However we need to further test and improve our detection scheme; quantify our incompleteness as a function of magnitude, position, and redshift; and importantly, add Spitzer photometry to help eliminate degeneracies between $z > 9$ and $z \sim 2$ galaxies.

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