A PILOT SURVEY FOR CIII\] EMISSION IN THE REIONIZATION ERA: GRAVITATIONALLY-LENSED $z \sim 7-8$ GALAXIES IN THE FRONTIER FIELDS CLUSTER ABELL 2744

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ABSTRACT

We report results of a search for CIII $\lambda\lambda 1907,1909$ Å emission using Keck’s MOSFIRE spectrograph in a sample of 7 $z_{\text{phot}} \sim 7-8$ candidates ($H \sim 27$) lensed by the Hubble Frontier Field cluster Abell 2744. Earlier work has suggested the promise of using the CIII doublet for redshift confirmation of galaxies in the reionization era given $\text{Ly}\alpha$ ($\lambda 1216$ Å) is likely attenuated by the neutral intergalactic medium. The primary challenge of this approach is the feasibility of locating CIII emission without advanced knowledge of the spectroscopic redshift. With an integration time of 5 hours in the H-band, we reach a 5σ median flux limit (in between the skylines) of $1.5 \times 10^{-18}$ ergs cm$^{-2}$ sec$^{-1}$ but no convincing CIII emission was found. We also incorporate preliminary measurements from two other CLASH/HFF clusters in which, similarly, no line was detected, but these were observed to lesser depth. Using the known distribution of OH emission and the photometric redshift likelihood distribution of each lensed candidate, we present statistical upper limits on the mean total CIII rest-frame equivalent width for our $z \sim 7-8$ sample. For a signal/noise ratio of 5, we estimate the typical CIII doublet rest-frame equivalent width is, with 95% confidence, $< 26\pm 5$ Å. Although consistent with the strength of earlier detections in brighter objects at $z \sim 6-7$, our study illustrates the necessity of studying more luminous or strongly-lensed examples prior to the launch of the James Webb Space Telescope.

Subject headings: galaxies: clusters: general, galaxies: high-redshift, gravitational lensing: strong, cosmology: observations, galaxies: evolution, galaxies: formation

1. INTRODUCTION

The reionization of the intergalactic medium (IGM) represents a key phase in the evolution of the Universe. Observations of high-redshift galaxies, which have charted a marked decline in the visibility of $\text{Ly}\alpha$ emission with redshift (Stark et al. 2010; Schenker et al. 2012), and those of $z > 5$ quasars which trace the redshift-dependent Gunn-Peterson absorption (Fan et al. 2006), indicate that cosmic reionization was largely complete by $z \sim 6$. The duration of the reionization process is constrained by the polarization of the microwave background due to Thomson scattering by electrons in the ionized era; recent data from the Planck satellite and results derived from the abundance and luminosity distribution of the $z > 6$ galaxy population now suggest reionization was a rapid process which extended over $6 < z < 10$ (Planck Collaboration et al. 2015; Robertson et al. 2015).

While $\text{Ly}\alpha$ emission ($\lambda 1216$ Å) has proven to be the most valuable spectroscopic indicator for faint star-forming galaxies in the redshift range $4 < z < 6$ (e.g. Stark et al. 2010, 2011), resonant scattering by neutral gas in the IGM likely renders this line ineffective as a reliable probe beyond $z \sim 6.5$. Despite much observational effort, there are currently very few convincing cases of detected $\text{Ly}\alpha$ emission beyond $z \sim 7$ (Ono et al. 2012; Finkelstein et al. 2013; Vanzella et al. 2014a; Schenker et al. 2014; Oesch et al. 2015) and several distant star-forming galaxies reveal no emission despite heroic exposure times (Vanzella et al. 2014b). As a result, Stark et al. (2014b) proposed it may be feasible to use metallic lines in the ultraviolet (UV) as alternative spectroscopic indicators. Examining the spectra of 17 gravitationally-lensed low-luminosity galaxies at $z \sim 1.5 - 3$, they discuss the feasibility of searching for CIII ($\lambda\lambda 1907,1909$ Å) and CIV ($\lambda\lambda 1548,1550$ Å) emission. Although such metallic lines are normally much weaker than $\text{Ly}\alpha$ in luminous systems, in young metal-poor low luminosity systems characteristic of those at high redshifts these lines may become relatively more prominent. In their sample of 17 $z \sim 1.5 - 3$ galaxies, Stark et al. (2014b) find CIII emission has an equivalent width (EW) which correlates with that of $\text{Ly}\alpha$ and is typically 10 times weaker. As an encouraging proof of concept, Stark et al. (2014a) recently claimed tentative detections of CIII emission in two $J \sim 25.2$ galaxies with pre-determined $\text{Ly}\alpha$ emission at redshifts of $z = 6.03$ and $z = 7.21$.

However, as emphasized by Stark and collaborators, detecting CIII emission in galaxies where its expected wavelength is a priori known from a $\text{Ly}\alpha$ redshift is less challenging than searching for emission across a wider range of wavelength governed only by a photometric redshift likelihood distribution, and given the density of skylines. Motivated by the interest in exploring the potential of this, possibly the only, immediate route to spectroscopic progress in the reionization era, we have embarked on a statistical search. Our plan is examine the spectra of a sample of gravitationally-lensed sources in the redshift range $z \sim 6.7-8.5$ derived from recent compilations in several massive clusters (e.g. Bradley et al. 2014; Atek et al. 2014b; Zheng et al. 2014; Coe et al. 2014). Such a statistical approach is now possible due to the arrival of multi-slit near-infrared spectrographs such as...
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2 hours in the Y-band, searching for Ly$\alpha$ and these data will be presented elsewhere.

Since CIII$\alpha$ is a doublet, we assume a line ratio CIII$\alpha_1/CIII\alpha_2$ of 1.4 (Stark et al. 2014a). We consider the probability of detecting at least one CIII$\alpha$ line in our survey, as a function of a given mean total flux and EW. No convincing line was seen for any of the 7 CIII$\alpha$ candidates. We thus seek to determine the likely range of fluxes and equivalent widths (EW) for CIII$\alpha$ consistent with our non-detections.

All reduced spectra were visually inspected given the expected wavelength range where CIII$\alpha$ might be visible according to the photometric redshift likelihood function. No convincing line was seen for any of the 7 CIII$\alpha$ candidates. We thus seek to determine the likely range of fluxes and equivalent widths (EW) for CIII$\alpha$ consistent with our non-detections. In other words, we estimate the probability of detecting at least one CIII$\alpha$ line in our survey, as a function of a given mean total flux and EW. Since CIII$\alpha$ is a doublet, we assume a line ratio CIII$\alpha_1/CIII\alpha_2$ of 1.4 (Stark et al. 2014a). We consider total line strengths in the range $0 - 4 \times 10^{-18}$ ergs cm$^{-2}$ sec$^{-1}$ in $5 \times 10^{-20}$ ergs cm$^{-2}$ sec$^{-1}$ increments as illustrated in Fig. 2. For each doublet line, and for each redshift step, we checked if its input flux would exceed a line flux limit, and the $3\sigma$ line flux limit, and the dashed blue and purple horizontal lines show fiducial input CIII$\alpha$ line fluxes. For each such iteration we measure the fraction (in wavelength) in which the input flux is higher than the observational limit, weighted by the photometric redshift distribution. This indicates the chance of seeing CIII$\alpha$, as elaborated in §3.

### RESULTS

Fig. 2.— Illustration of the data. The top panel shows an arbitrary reduced slit in A2744, centered vertically on the CIII$\alpha$ candidate. The middle panel shows the extracted 1D spectrum (blue), and its $1\sigma$ error (red) – both smoothed here for illustrative purposes. The bottom panel shows an arbitrary reduced slit in A2744, centered vertically on the CIII$\alpha$ candidate. The horizontal lines show fiducial input CIII$\alpha$ line fluxes. For each such iteration we measure the fraction (in wavelength) in which the input flux is higher than the observational limit, weighted by the photometric redshift distribution. This indicates the chance of seeing CIII$\alpha$, as elaborated in §3.

$P_{\text{det},k}(F_{\text{in}}, x) = \frac{\sum_k P_k(z_i) \Theta (F_{\text{in}}, x, \sigma_k, z_i)}{\sum_k P_k(z_i)}$, (1)

where the sum is over all the redshift steps $z_i$ ($z = 0$ to $z = 12$ in 0.001 increments), and $\Theta$ is defined as

$\Theta (F_{\text{in}}, x, \sigma_k, z_i) = \begin{cases} \frac{1}{\sigma_k} & \text{if } F_{\text{in}} > x \sigma_k \cdot 1907\text{Å} \cdot (1 + z_i) \\ 0 & \text{otherwise} \end{cases}$

and we define $\sigma_k = \infty$ for $z_i$ steps placing the line outside the MOSFIRE $H$ band. $P_{\text{det},k}$ therefore provides a conditional probability, i.e. the chance of detecting at least one of the two CIII$\alpha$ lines for a given target $k$ with

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6 We note that A2744 was also observed with the same mask for 2 hours in the Y-band, searching for Ly$\alpha$. No line was detected and these data will be presented elsewhere.
redshift probability distribution $P_k(z)$, given the limiting noise in our spectra for the mask, $\sigma_k(\lambda)$ (see §2), and as a function of the input line flux $F_{in}$ and the detection significance $x$. Finally, the probability of detecting at least one line of a given flux $F_{in}$ over the entire sample is:

$$P_{\text{sample}}(F_{in}, x) = 1 - \prod_k (1 - P_{\text{det,k}}(F_{in}, x)),$$

where the product is over all slits.

We repeat the above process also in terms of restframe EW, where in each iteration, instead of running over a range of input fluxes, we run over a range of restframe EWs, translated in each iteration, for each object individually, to the corresponding input flux.

Figure 3 shows the probability, for both 3 and 5 $\sigma$ detections, of finding at least one line in our A2744 survey as a function of the mean total CIII] flux and restframe EW. For example we have a 95% chance of detecting at least one CIII] line in our MOSFIRE survey at $5\sigma$ significance, if the typical CIII] $\lambda 1907$ Å line flux is $\simeq 1.5 \times 10^{-18}$ ergs cm$^{-2}$ sec$^{-1}$ (total doublet flux of $\simeq 2.6 \times 10^{-18}$ ergs cm$^{-2}$ sec$^{-1}$), or equivalently, if the rest-frame EW for the combined CIII] doublet is 26 $\pm$ 5 Å or higher. In this estimate we have included limits...
from the shallower exposures on A2261 and M0416, but
the results remain similar (to within typically 5%) if the
sample is restricted to A2744 – for which photometric
redshift errors are typically smaller and the observations
are significantly deeper. Errors were propagated assum-
ing our adopted 20% uncertainty in the flux calibration.

For comparison, Stark et al. (2014a) detected, with
$3.3\sigma$, a $\Lambda 1909$ A CIII] line of $\sim 4.2 \pm 1.2 \times 10^{-18}$ ergs
cm$^{-2}$ sec$^{-1}$ (total estimated CIII] flux $\sim 1.1 \pm 0.3 \times 10^{-17}$) in a $z = 6.03$ galaxy ($J = 25.2$), and a $2.8\sigma$ CII]
detection of likely $\Lambda 1909$ A of $\sim 0.9 \pm 0.3 \times 10^{-18}$ ergs
cm$^{-2}$ sec$^{-1}$ (total estimated CIII] flux $\sim 2.3 \pm 0.5 \times 10^{-18}$) in a $z = 7.21$ galaxy ($J = 25.2$). The total CIII]
rest-frame EWs of these detections are $22.5 \pm 7.1$ Å and
$7.6 \pm 2.8$ Å respectively.

While our observational limits are deep enough to re-
cover similar line fluxes to those found by Stark et al.
(2014a, see also Stark et al. 2014b), our galaxies are
taller ($\sim 27$ AB), so that our limits on the rest-
frame EWs are less constraining. Assuming a CIII] EW of
$22.5(7.6)$ Å as was found by Stark, we have
$\sim 99.9\%$ (10\%) chance for detecting at least one such line
in our sample with $3\sigma$, or $\sim 90\%$ (0\%) for $5\sigma$. Thus, it is
quite likely that the primary reason for the non-detection
in our survey is that, on average, the present sample
is significantly fainter than those targeted by Stark et al.,
which also had the benefit of secure Lyman-based red-
shifts. The main conclusion of our limits seen in Figures
3 and 4 is that even with a more ambitious spectroscopic
campaign that would likely increase the exposure time
by a factor $\times 4$ (corresponding to a 3 night integration
on one mask), only more luminous $z \sim 7-8$ galaxies in the
reionization era would appear to be amenable for study
with any reliability. Alternatively, brighter and/or
more highly-magnified examples, such as those close
to the critical line of a foreground cluster, might provide
promising targets although generally such sources are
rare. It is interesting to note the non-detection (and up-
per limit) on CIII] emission recently claimed by Watson
et al. (2015) for a brighter source with $H=24.7$, mag-
nified by $\mu \sim 10$ at $z=7.5$, showing that even for sig-
nificantly brighter objects CIII] detection can be chal-
lenging. Searching for bright magnified dropouts in a
very large sample of clusters, for example, is desirable
for progress with current facilities and might help deliver
JWST with first light targets.

For completeness, we also calculate the limit on the
CIV $\lambda\lambda (1548,1550)$ Å doublet for the $z \sim 9.8$ multiply-
imaged object discovered by Zitrin et al. (2014) behind
A2744 (Fig. 3). Stark et al. (2014b) found prominent
CIV emission in some of the $z \sim 2$ galaxies they targeted,
and highlighted CIV as an additional promising diag-
nostic for high-redshift galaxies. Typically they found CIV
line fluxes only a factor of about 2 weaker than those of
CIII]. At the proposed redshift of the Zitrin et al. (2014)
object, the doublet would be readily resolved and we
assume both lines have equal strength. In this case, we
determine that, with $\sim 90\%$ confidence, the line flux for
either one of the two CIV lines for a detection signifi-
cance of $5\sigma$ is less than $\sim 3.6 \times 10^{-18}$ ergs cm$^{-2}$ sec$^{-1}$, and
the rest-frame EW less than $\sim 32$ Å. This trans-
lates to a magnification-corrected, total CIV luminosity

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{The rest-frame EW as a function of absolute UV magnitude,
of previous measurements of CIII] from Stark et al. (2014b,a).}
\end{figure}

4. CONCLUSIONS

Given the attenuation of Ly$\alpha$ by neutral gas in the
reionization era, the CIII] doublet has been proposed as
a promising route toward spectroscopic verification
and study of high-redshift candidates (Stark et al.
2014a,b). We report results from a short campaign
with Keck/MOSFIRE to assess the prospects of detect-
ing CIII] lines in a sample of faint gravitationally-lensed
$z \sim 7-8$ galaxies where Ly$\alpha$ is not seen and thus
the search window in wavelength is much larger than in ear-
lier work. We observed 14 high-$z$ candidates magnified
by three galaxy clusters. For our deepest field (A2744, with
7 CIII] candidates), we reached a $5\sigma (3\sigma)$ flux limit
of $1.5(0.9) \times 10^{-18}$ ergs cm$^{-2}$ sec$^{-1}$ but did not detect
any convincing line. Using a statistical method employ-
ing data from our collective campaign, we provide upper
limits on the typical CIII] line flux and its rest-frame EW.
Although our limits reach the line fluxes observed in some
actual CIII] detections claimed in the recent literature,
because our sample is significantly fainter in apparent
magnitude, we only marginally reach the expected EWs
based on these recent detections. This demonstrates the
challenge of continuing the present investigation with
current observing facilities unless either (i) brighter or
more strongly-lensed sources are targeted and/or (ii) the
CIII] is found to be more prominent in intrinsically-
fainter systems (e.g. Stark et al. 2014b). More data is
needed to test this latter suggestion.
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REFERENCES

Robertson, B. E., Ellis, R. S., Furlanetto, S. R., & Dunlop, J. S. 2015, arXiv, 1502.02024
Stark, D. P., Walth, G., Charlot, S., et al. 2015, arXiv, 1504.06881
### TABLE 1

The Sample

<table>
<thead>
<tr>
<th>ID</th>
<th>α(deg.)</th>
<th>δ(deg.)</th>
<th>Phot-z</th>
<th>$H_{160}$</th>
<th>μ</th>
<th>β</th>
<th>$M_{UV,1500}$</th>
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</thead>
<tbody>
<tr>
<td>A2744-YD7(a, b)</td>
<td>3.603397</td>
<td>-30.382256</td>
<td>8.3(\pm0.1)</td>
<td>26.17 ± 0.03</td>
<td>1.4(\pm0.7)</td>
<td>-1.38 ± 1.86</td>
<td>-20.65(\pm0.54)</td>
</tr>
<tr>
<td>A2744-ZD3(a, b, c)</td>
<td>3.606477</td>
<td>-30.380993</td>
<td>7.7(\pm0.2)</td>
<td>26.45 ± 0.04</td>
<td>1.3(\pm0.1)</td>
<td>-1.14 ± 0.26</td>
<td>-20.19(\pm0.19)</td>
</tr>
<tr>
<td>A2744-ZD9(a)</td>
<td>3.603208</td>
<td>-30.410368</td>
<td>7.0(\pm0.2)</td>
<td>26.48 ± 0.04</td>
<td>3.4(\pm0.8)</td>
<td>-1.17 ± 0.23</td>
<td>-18.88(\pm0.37)</td>
</tr>
<tr>
<td>A2744-ZD7A2(a)</td>
<td>3.592160</td>
<td>-30.400925</td>
<td>7.3(\pm0.5)</td>
<td>28.18 ± 0.04</td>
<td>6.4(\pm1.3)</td>
<td>-1.29 ± 1.22</td>
<td>-16.63(\pm0.42)</td>
</tr>
<tr>
<td>A2744-YD8(a, b, c)</td>
<td>3.596096</td>
<td>-30.385832</td>
<td>8.1(\pm0.1)</td>
<td>26.65 ± 0.04</td>
<td>1.9(\pm0.2)</td>
<td>-1.84 ± 1.64</td>
<td>-19.86(\pm0.57)</td>
</tr>
<tr>
<td>Atek-3772(c)</td>
<td>3.5978343</td>
<td>-30.395960</td>
<td>7.0(\pm0.6)</td>
<td>27.45 ± 0.05</td>
<td>~6.8</td>
<td>-1.77 ± 1.00</td>
<td>-17.51(\pm0.24)</td>
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<tr>
<td>Atek-5918(a, c)</td>
<td>3.5951375</td>
<td>-30.381131</td>
<td>7.7(\pm0.6)</td>
<td>26.92 ± 0.02</td>
<td>~3.5</td>
<td>-1.07 ± 0.19</td>
<td>-18.65(\pm0.27)</td>
</tr>
<tr>
<td>A2744-JDB(d)</td>
<td>3.5950200</td>
<td>-30.400750</td>
<td>9.8(\pm0.4)</td>
<td>27.30 ± 0.07</td>
<td>11.3(\pm2.5)</td>
<td>...</td>
<td>~17.6</td>
</tr>
<tr>
<td>A2261-0450(f)</td>
<td>260.6124593</td>
<td>32.1438429</td>
<td>6.8(\pm0.3)</td>
<td>25.5 ± 0.06</td>
<td>~5.6</td>
<td>-1.85 ± 0.15</td>
<td>-19.50(\pm0.23)</td>
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<td>A2261-0731(f)</td>
<td>260.6232556</td>
<td>32.1393984</td>
<td>6.9(\pm0.9)</td>
<td>27.9 ± 0.22</td>
<td>~7.7</td>
<td>-1.00 ± 0.67</td>
<td>-16.65(\pm0.34)</td>
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<tr>
<td>A2261-0772(f)</td>
<td>260.6059024</td>
<td>32.1388049</td>
<td>6.5(\pm5.4)</td>
<td>27.4 ± 0.19</td>
<td>~6.3</td>
<td>-2.17 ± 0.64</td>
<td>-17.35(\pm0.30)</td>
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<tr>
<td>A2261-0187(f)</td>
<td>260.6073833</td>
<td>32.1495175</td>
<td>7.5(\pm4.2)</td>
<td>27.0 ± 0.13</td>
<td>~2.9</td>
<td>-1.18 ± 1.47</td>
<td>-18.89(\pm0.25)</td>
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<tr>
<td>MACS0416-0036(f)</td>
<td>64.0260447</td>
<td>-24.0509958</td>
<td>7.0(\pm6.0)</td>
<td>26.8 ± 0.16</td>
<td>~1.3</td>
<td>-0.56 ± 0.45</td>
<td>-19.46(\pm0.42)</td>
</tr>
<tr>
<td>Zheng-4408(g)</td>
<td>64.0603330</td>
<td>-24.064960</td>
<td>7.7(\pm0.3)</td>
<td>27.85 ± 0.08</td>
<td>2.2(\pm0.3)</td>
<td>-3.49 ± 1.33</td>
<td>-18.59(\pm0.28)</td>
</tr>
<tr>
<td>FCC2-1151-4540(h, g)</td>
<td>64.0479780</td>
<td>-24.081678</td>
<td>8.3(\pm0.2)</td>
<td>26.59 ± 0.03</td>
<td>1.8(\pm0.5)</td>
<td>-1.44 ± 0.69</td>
<td>-19.93(\pm0.31)</td>
</tr>
</tbody>
</table>

**Note.** —

Column 1: Dropout’s ID and references. The first work cited for each object represents the original source of photometric data and analysis, although in some cases we made adjustments to enhance consistency across the sample.


Column 4: Photometric redshift and 95% errors.

Column 5: HST’s apparent $H_{160}$-band magnitude.

Column 6: Lensing magnification. If no error is listed a nominal ~20% error is adopted (Zitrin et al. 2015).

Column 7: UV-slope, β (1σ errors), calculated by a weighted least-squares fit.

Column 8: Absolute magnitude, $M_{UV}$, at $λ = 1500$ Å, calculated from the said $F_λ ∝ λ^β$ fit, where the error includes in quadrature the discrepancy from the absolute magnitude obtained by translating the flux in the WFC3 band containing the redshifted $λ = 1500$ Å, and the propagated photometric and magnification errors.

\(a\) Zheng et al. (2014)

\(b\) Coe et al. (2014)

\(c\) Atek et al. (2014a)

\(d\) Zitrin et al. (2014). CIV target.

\(e\) Our independent photo-z estimate permits a solution at $z \approx 2$

\(f\) Bradley et al. (2014)

\(g\) W. Zheng, private communication (in preparation).