*Galaxies at High Redshift and Their Evolution Over Cosmic Time*
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# Probing Reionization at $z \gtrsim 7$ with *HST*'s Near-Infrared Grisms

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**Abstract.** The epoch of reionization, i.e. the phase transition of the inter-galactic medium from neutral to fully ionized, is essential for our understanding of the evolution of the Universe and the formation of the first stars and galaxies. The Grism Lens-Amplified Survey from Space (GLASS) has obtained spectra of ten thousands of objects in and behind 10 massive galaxy clusters, including the six Hubble Frontier Fields. The grism spectroscopy from GLASS results in hundreds of spectra of $z \gtrsim 7$ galaxy candidates. Taking advantage of the lensing magnification from the foreground clusters, the GLASS spectra reaches unprecedented depths in the near-infrared with *observed* flux limits of $\sim 5 \times 10^{-18}$erg/s/cm$^2$ before correcting for the lens magnification. This has resulted in several Ly$\alpha$ detections at $z \sim 7$ and tight limits on the emission line fluxes for non-detections. From an ensemble of different photometric selections, we have assembled more than 150 $z \gtrsim 7$ galaxy candidates from six of the ten GLASS clusters. Among these more than 20 objects show emission lines consistent with being Ly$\alpha$ at $z \gtrsim 7$. The spatial extent of Ly$\alpha$ estimated from a stack of the most promising Ly$\alpha$ emitters at $\langle z \rangle = 7.2$ is consistent with the spatial extent of the UV continuum emission. From the stack we obtain upper limits on the emission line ratios between prominent rest-frame UV emission lines, finding that $f_{\mathrm{CIV}}/f_{\mathrm{Ly}\alpha} \lesssim 0.32$ and $f_{\mathrm{CIII]}}/f_{\mathrm{Ly}\alpha} \lesssim 0.23$ in good agreement with values published in the literature.

**Keywords.** infrared: galaxies, techniques: spectroscopic, galaxies: high-redshift, galaxies: inter-galactic medium, line: identification

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**GLASS Overview:**

The Grism Lens-Amplified Survey from Space (GLASS) resented by Schmidt *et al.* (2015) and Treu *et al.* (2015) has targeted 10 massive galaxy clusters including the 6 Hubble Frontier Fields (PI Lotz) and 8 CLASH clusters presented by Postman *et al.*, (2012). GLASS observed each of the cluster cores with the two near-infrared *HST* WFC3 grism G102 and G140 accompanied by a direct image pre-exposure in either the F105W or F140W filter. The parallel fields were observed in the optical with the ACS grism G800L with a matching direct image in the F814W filter. This has resulted in slitless spectroscopy of roughly 2000 individual objects in the cluster field of each cluster, including both cluster galaxies, foreground low-redshift galaxies, spatially resolved lensed galaxies at intermediate redshifts, and galaxies at the epoch of reionization with redshifts $z > 6$. With the near-infrared grisms, GLASS covers the Ly$\alpha$ line in a redshift range from approximately 5.6 all the way out to a Ly$\alpha$ redshift of 13. The GLASS filter/grism set, their wavelength coverage, and the Ly$\alpha$ redshift range probed on the cluster cores are shown in Figure 1. The GLASS data were taken at two distinct position angles roughly 90 degrees apart to optimize accounting for contaminating flux from neighboring object in the crowded cluster fields and to aid the detection and identification of emission lines in the spectra. Each of the spectra reach $1\sigma$ flux limits of $5 \times 10^{-18}$erg/s/cm$^2$ before the two spectra from the two position angles are combined (which lowers the flux limits by $\sqrt{2}$) and the lensing magnification, $\mu$, is accounted for (which further lowers the flux limits by a factor $\mu$) as presented by Schmidt *et al.* (2014), Schmidt *et al.* (2015) and

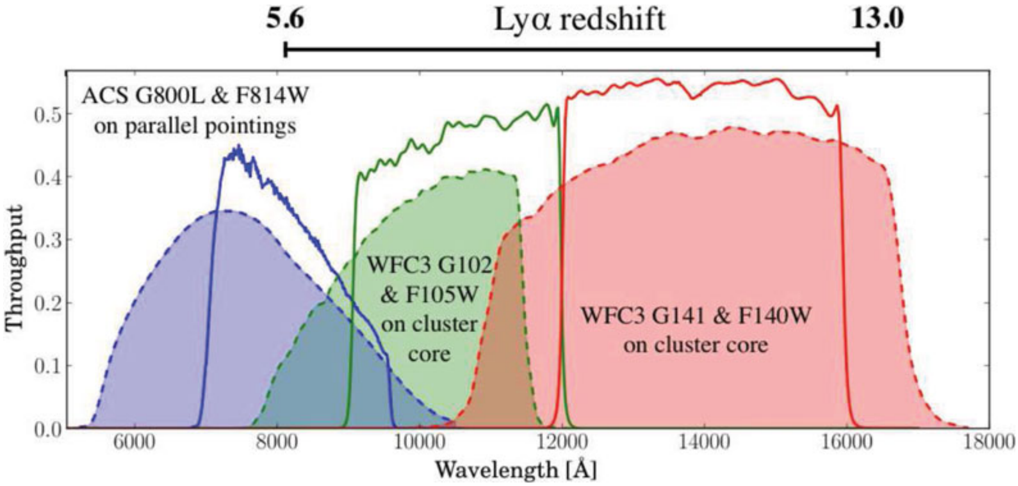


**Figure 1.** The *HST* broad band and grism throughput curves used in by GLASS. The near-infrared filters and grisms were pointed at the 10 cluster cores at two different position angles roughly 90 degrees apart, providing slitless spectroscopy and pre-imaging of roughly 20000 objects in, as well as behind, the massive galaxy clusters. The optical ACS imaging and spectroscopy was optioned from the corresponding parallel pointings. The bar at the top marks the redshift range at which the Ly$\alpha$ line from background sources in the cluster core can be observed.

Treu *et al.* (2015). GLASS was designed to address three main science questions, namely i) how did galaxies reionize the Universe (if they did)? ii) how do metals cycle in an out of galaxies? and iii) what effect does the environment have on galaxy evolution of cluster and field galaxies? A study and exploration of the epoch of reionization and the likely reionizing galaxies inhabiting these early stages of the Universe, is enabled by the lens-improved spectroscopic depths of the hundreds of high-redshift objects behind the GLASS clusters. In the following we will summarize and present the results from the first study addressing GLASS science driver i) as presented by Schmidt *et al.* (2015).

**Selecting $z \gtrsim 7$ Galaxies:** From six of the ten GLASS clusters we assembled a sample of $z \gtrsim 7$ galaxy candidates from photometric redshifts, and generating an ensemble of Lyman break galaxies from more than 15 different dropout selections and collecting high-redshift galaxy candidates presented in the literature. This resulted in more than 150 photometrically selected objects at $z \gtrsim 7$. The individual GLASS spectra for all of these objects were visually inspected by the GLASS team, searching for Ly$\alpha$ emission. In ~15% of the objects we found emission lines consistent with being Ly$\alpha$ at $z \gtrsim 7$. The modest resolution of the *HST* near-infrared grisms ($R \sim 100 - 200$) does not allow the detection of the asymmetry of the Ly$\alpha$ line to definitely confirm the detected emission to be Ly$\alpha$. We are currently leading several large high-resolution ground-based spectroscopic follow-up programs to confirm the high-redshift nature of these sources.

**Stack of Ly$\alpha$ Emitters at $\langle z \rangle = 7.2$:** The opacity of Ly$\alpha$ has been shown to increase in the increasingly neutral inter-galactic and/or circus-galactic medium at redshifts above 7 by, e.g., Treu *et al.* (2012), Treu *et al.* (2013), Pentericci *et al.* (2014), Tilvi *et al.* (2014). It has recently been speculated that alternative rest-frame UV emission lines like CIII] and CIV, which are unaffected by the amount of neutral hydrogen in the circum-galactic and inter-galactic media, can be used to detect high redshift galaxies Stark *et al.*

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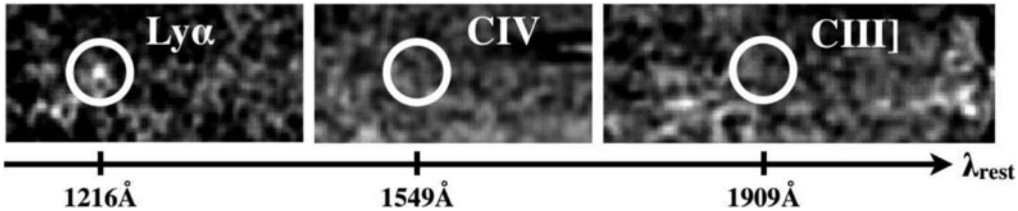


**Figure 2.** The rest-frame stack of promising Ly$\alpha$ emitters at $\langle z \rangle = 7.2$ from Schmidt *et al.* (2015). No CIV and CIII] emission is detected. The spatial profile (vertical direction) of the Ly$\alpha$ emission is comparable to that of the continuum UV emission. Any extended Ly$\alpha$ emission is below the surface brightness detection threshold in the stack as shown in Figure 3.

(2014), Stark *et al.* (2015a) and Stark *et al.* (2015b). To enhance the signal-to-noise potential detection of these rest-frame UV lines, we stacked the most promising Ly$\alpha$ emitters. The stack has a mean redshift of $\langle z \rangle = 7.2$, and is show in Figure 2 at the rest-frame wavelengths of Ly$\alpha$, CIV and CIII]. The Ly$\alpha$ is (obviously) clearly detected, but we do not detect any CIV or CIII] emission in the stack. From the GLASS stack we obtain limits on the emission line flux ratios of $f_{\rm CIV}/f_{\rm Ly\alpha} \lesssim 0.32$ and $f_{\rm CIII]}/f_{\rm Ly\alpha} \lesssim 0.23$. These limits are in good agreement with low and intermediate-redshift detections from the literature by, e.g., Shapley *et al.* (2003), Erb *et al.* (2010) and Stark *et al.* (2014), Stark *et al.* (2015a), Stark *et al.* (2015b).

From the stacked slitless grism spectra shown in Figure 2 we extracted the spatial profile of the Ly$\alpha$ line, which is shown as the green curve in the top left panel of Figure 3. Similarly, we stacked the direct rest-frame UV images of the Ly$\alpha$ emitters and extracted the spatial profile from this stack, represented by the green curve in the top right panel. Comparing these two profiles with the grism point spread function represented by the spatial profile of a stack of stars in the GLASS field-of-views, shows that they are both unresolved, and we do therefore not detect any extended Ly$\alpha$ in the stack. Furthermore, we find no evidence for a difference in the spatial extent of the Ly$\alpha$ emission and the UV continuum at $\langle z \rangle = 7.2$. The Ly$\alpha$ emission in galaxies at lower redshifts have been shown to have larger spatial extent than the corresponding UV continuum emission. In the Ly$\alpha$ Reference Sample (LARS) presented by Östllin *et al.* (2014) and Hayes *et al.* (2013) this is also true. Following the recipes described by Guaita *et al.* (2015), we simulate the LARS sample to be at $z = 7.2$. A comparison of the spatial profiles of these galaxies (shown in magenta in the bottom panels of Figure 3) to the results from the GLASS stack, show that we would not expect to detect the extended Ly$\alpha$ emission, as it falls below the surface brightness detection limit of the GLASS stack. For details on this comparison see Schmidt *et al.* (2015) and the proceeding for *XXIXth IAU General Assembly Focus Meeting 22.2.02*.

**In Summary** the GLASS data acquisition on 10 massive galaxy clusters, including HFF and CLASH clusters, is completed, and the data products have started to be released to the public through https://archive.stsci.edu/prepds/glass/. The data reaches *observed* $1\sigma$ flux limits of $\sim 5 \times 10^{-18}$erg/s/cm$^2$. From the first six completed clusters $> 150$ $z \gtrsim 7$ galaxy candidates have been presented in Schmidt *et al.* (2015). This sample includes 24 potential Ly$\alpha$ emitters. In a stack ($\langle z \rangle = 7.2$) of the most promising Ly$\alpha$ emitters no CIV and CIII] as well as no spatially extended Ly$\alpha$ emission is detected.

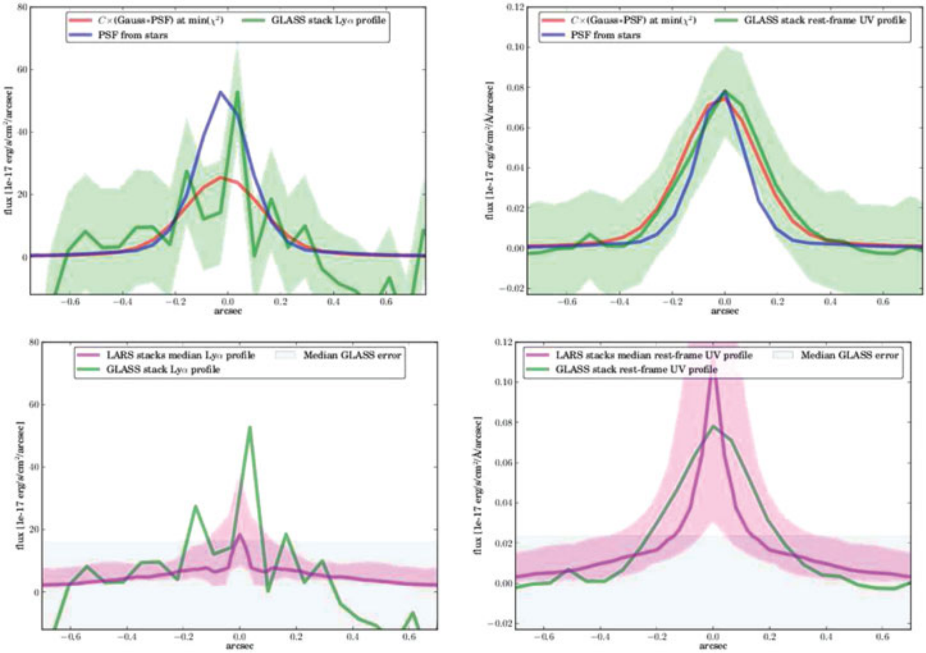


**Figure 3.** The top panels show the spatial profiles of the stacked Ly$\alpha$ emitters at $\langle z \rangle = 7.2$ shown in Figure 2 (left, green curve) and their observed NIR (rest-frame UV) direct images (right, green curve). These profiles are compared to the PSF represented by the spatial profile of stars (blue curves) in the GLASS filed-of-views. The red curves in the top panels show the convolved PSF (multiplied by a constant $C$) that minimizes the $\chi^2$ between the PSF and the data. Both the Ly$\alpha$ and the rest-frame UV profiles from the GLASS stacks are unresolved closely resembling the rest-frame UV profile. Hence, taken at the face value, there is no evidence that the spatial extent of Ly$\alpha$ is more extended than the UV light in the GLASS stack. The bottom panels show a comparison to the median LARS Ly$\alpha$ and rest-frame UV profiles at $z = 7.2$. The shaded area around the profiles shows the $1\sigma$ spread of the individual profiles. The median error on the GLASS stacks (from the top panel's green shaded region) is represented by the gray band. Based on this comparison, we conclude that the extended Ly$\alpha$ emission surface brightness typical of lower-redshift Lyman break galaxies is too faint to be detected in this GLASS stack. Figure taken from Schmidt *et al.* (2015).

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