# Evolution of the Observed Lyα Luminosity Function from $z = 6.5$ to $z = 7.7$: Evidence for the Epoch of Re-ionisation?

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**Probing the first billion years of the Universe is one of the last frontiers in cosmology. Lyα emitters (LAEs) are galaxies that can be detected out to very high redshifts during the epoch of re-ionisation. The evolution of their luminosity function with redshift is a direct probe of the Lyα transmission of the intergalactic medium (IGM), related to the amount of neutral hydrogen. We report on the results of a search for LAEs at $z = 7.7$ using HAWK-I at the VLT with a narrowband filter centred at 1.06 µm. We did not find any LAE candidates, which allows us to infer robust constraints on the LAE luminosity function at $z = 7.7$. Depending on which luminosity functions at $z = 6.5$ are referred to, our results may reflect a significant quenching of the IGM Lyα transmission, possibly from a strong increase in the neutral hydrogen fraction between these two redshifts.**

The quest for distant objects has made spectacular progress since the discovery of the first astrophysical object at a redshift > 6, a Lyα emitter at redshift 6.56 (Hu et al., 2002). For finding high-redshift galaxies, astronomers mainly use two techniques based on optical and infrared imagery data. The Lyman-break technique uses the redshifting of the Lyα forest to locate strong absorption breaks in broadband photometry of galaxies (Lyman break galaxies – LBGs), while the narrowband (NB) technique looks for a photometric excess in NB filters due to the redshifted Lyα line. NB filters are usually designed to coincide with regions of low OH emission of the night sky, leading to discrete redshift values. At $z = 5.7$ and $z = 6.5$, the largest samples of LAEs were obtained with the SuprimeCam on the Subaru Telescope (Ouchi et al., 2010; Hu et al., 2010; Kashikawa et al., 2010). Large samples of LBGs at redshift > 7 have been recently assembled from Hubble Space Telescope (HST) observations with the new WFC3 near-infrared camera. Similarly, quasars at high redshift are found using the Lyman-break technique in multi-colour datasets over very wide fields, such as the Sloan Digital Sky Survey. Finally, gamma-ray bursts (GRBs) have been discovered at very high redshift and nicely complement the other methods by probing the faint end of the galaxy luminosity function.

## Probing the epoch of re-ionisation

Observations of the cosmic microwave background (CMB) allow astronomers to constrain the history of re-ionisation. Polarisation measurements of the CMB from WMAP show a large optical depth due to Thomson scattering of CMB photons from free electrons in the early Universe, suggesting that the re-ionisation started 500 million years after the Big Bang at redshift 10.6 ± 1.2 (Komatsu et al., 2011). Conversely, the strong increase of the optical depth in the Lyα forest of high-redshift quasars is a likely indicator that re-ionisation was mostly complete at a redshift of ~ 6. Determining how and at what pace the re-ionisation process took place when the Universe was 500 Myr to 1 Gyr old are the key questions that motivate the search for high-redshift objects.

Due to the resonant nature of the Lyα line ($\lambda = 121.6$ nm), Lyα photons are easily affected by neutral hydrogen on their path to the observer and are scattered out of the line of sight. Thus, it has long been proposed that Lyα transmission by the intergalactic medium (IGM) could be used as a probe of its ionisation state during the re-ionisation epoch. One observational method of probing Lyα IGM transmission is to study the evolution of the LAE luminosity function (LF) with redshift. Various results show that the Lyα LAE LF remains surprisingly unchanged from $z \sim 2$ to $z \sim 6$. Ouchi et al. (2010) and Kashikawa et al. (2011) infer from their NB observations that the evolution of the LAE LF between $z = 5.7$ and 6.5 can be attributed to a reduction of the IGM Lyα transmission of the order of 20%, which can in turn be attributed to a neutral hydrogen fraction $x_{HI}$ of the order of 20% at $z = 6.5$. Hu et al. (2010) have recently questioned this result and report significantly different LF parameters. They report lower number counts and no evolution in luminosity between $z = 5.7$ and $z = 6.5$. These somewhat discrepant observational results could tentatively be attributed to cosmic variance or to differences in the selection criteria and in extrapolations of the spectroscopic samples to photometric samples. New data at redshift ~ 6 will help in resolving the current contention, while data at higher redshifts can bring new constraints at still poorly explored redshifts.

This paper (see Clément et al. [2011] for full details) presents new results on the LAE luminosity function at $z = 7.7$, from observations carried out at the VLT with the HAWK-I instrument (Casali et al., 2005).

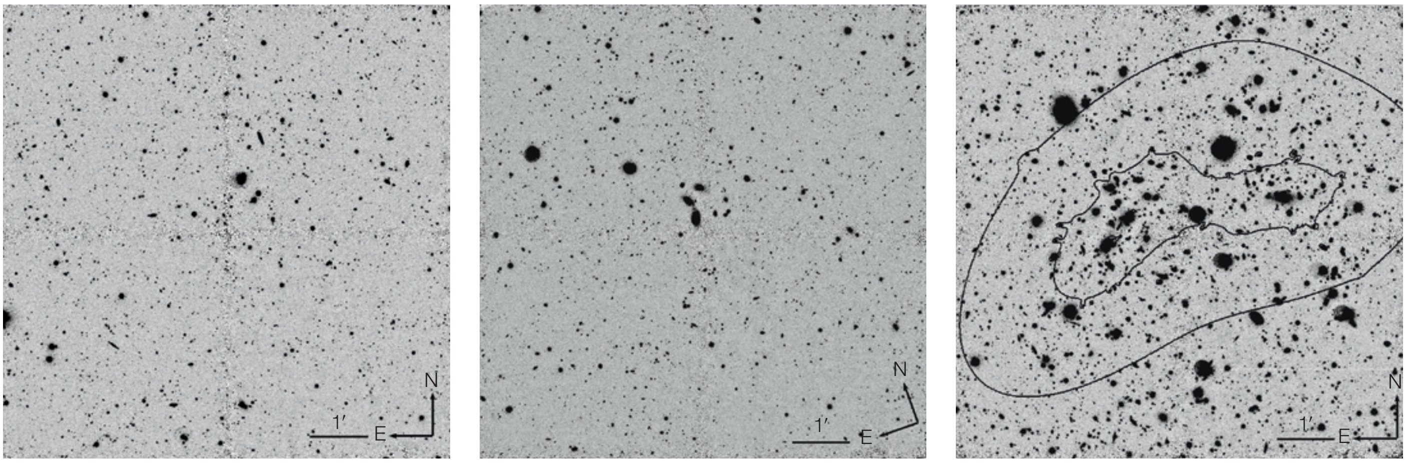


Figure 1. Images of the CFHTLS-D4 (left panel), GOODS-S (middle panel), and Bullet Cluster (right panel) fields as in the final HAWK-I *NB1060* image stacks. The inner and outer black contours on the Bullet Cluster image represent the regions where the gravitational amplification is respectively greater than 2.5 and greater than 1.2 for a source at a redshift of 7.7.

## Narrowband observations at 1.06 μm

Thanks to its wide field of view (7.5 by 7.5 arcminutes), excellent throughput and image quality, HAWK-I is ideally suited to searching for faint near-infrared (NIR) objects such as very high-redshift galaxies. The main dataset was obtained through a dedicated ESO large programme between September 2008 and April 2010. It is primarily based on observations using a NB filter at 1.06 μm (hereafter referred to as *NB1060*). In addition, we include in our analysis HAWK-I science verification NB data taken in 2007. High-redshift galaxies can be extremely faint, and thus an efficient way to detect the faintest objects is to make use of massive galaxy clusters as gravitational telescopes. The amplification provided by gravitational lensing of background sources by foreground galaxy clusters allows us to probe luminosities that are intrinsically fainter than in the field, but at the expense of areal coverage due to space distortion.

We performed a careful analysis of the relative merits of blank field and cluster fields and determined that observing two clusters and two blank fields would be optimal in terms of high-redshift LAE yield, while mitigating the effects of cosmic variance. Our selected fields were Abell 1689 and 1E0657-56 (Bullet Cluster) for the cluster fields, the northern half of the GOODS-S field and a subarea of the one square degree CFHTLS-D4 field for the two blank fields. The fields were chosen for the wealth of the available archival data. For one field, Abell 1689, it proved hard to assemble a consistent multi-wavelength dataset covering the full 7.5 by 7.5 arcminute HAWK-I field of view; this field will therefore be analysed separately and is not included in the present analysis. Figure 1 presents finding charts of the three fields studied here.

Our large programme data consists of more than 110 hours of on-sky integration time, of which ~ 80 hours are *NB1060* data. Figure 2 shows the overall transmission curves of the HAWK-I broadband and NB filters corresponding to these observations. The *NB1060* filter has a central wavelength of 1062 nm, a full width at half maximum (FWHM) of $\Delta\lambda \sim 10$ nm and is designed to match a region of low OH emission from the night sky. The filter width samples the Lyα line between $z = 7.70$ and $z = 7.78$. For each field, the *NB1060* data are acquired over two epochs separated by one year, allowing us to discard transient objects that could be detected in a one-epoch stack, and not in the other. The three *NB1060* final images have exquisite image qualities ranging from 0.53 to 0.58 arcseconds. The 3σ *NB1060* point source detection limits are 26.65, 26.65, and 26.50 for the GOODS-S, CFHTLS-D4, and Bullet Cluster respectively, in AB magnitudes.

## Candidate selection

We do not expect $z = 7.7$ LAEs to be detected in any of the filters blueward of the Lyα line redshifted to 1.06 μm. First, negligible amounts of radiation are expected to escape the galaxy and to be transmitted by the IGM below the Lyman limit at 91.2 nm, which is redshifted to ~ 790 nm. In addition, all the radiation between the Lyα and Lyγ lines at $z = 7.7$ is entirely redshifted beyond the Gunn–Peterson trough at ~ 850 nm observed in the spectra of high-redshift quasars and which corresponds to the end of the re-ionisation at $z \sim 6$. Only the blue part of the Lyα forest, just above the Lyman limit, could be transmitted to Earth. In practice, considering the limiting magnitudes of our optical and *NB1060* images, absorption of 2 magnitudes or so will result in no detections in any of the optical bands.

We used SExtractor for source detection and photometric measurements. We built a master catalogue of all the *NB1060* detected objects, measuring their magnitudes in each of the optical and NIR broadband images by running SExtractor in double image mode. We then searched for objects in this master catalogue that are not detected in the optical images at a signal-to-noise ratio above two. Because the *NB1060* bandpass is located within the bandpass of the *Y* filter (see Figure 2), the Lyα line may be detected in the *Y* filter when data in this filter are available. To estimate the *Y-NB1060* colour as a function of redshift, we generated simple synthetic models of LAE spectra and find that for objects with redshifts correspond-

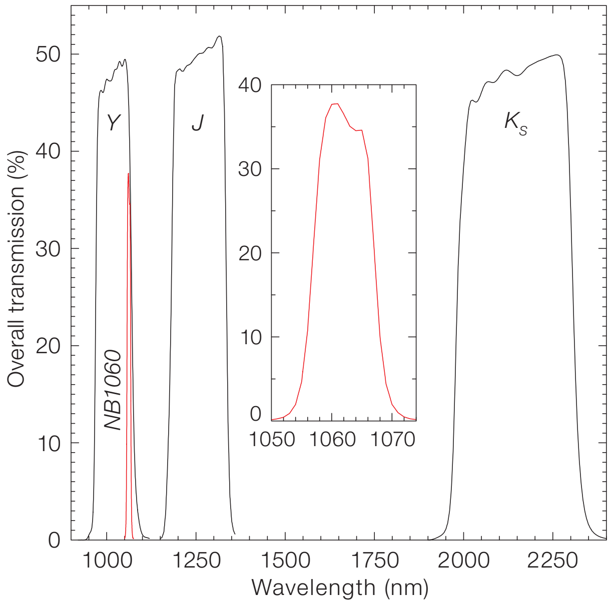


Figure 2. Transmission curves of the HAWK-I broadband and narrowband filters corresponding to the observations made as part of our large programme. The red curve and the inset show the profile of the *NB1060* filter centred at the wavelength of 1060 nm.

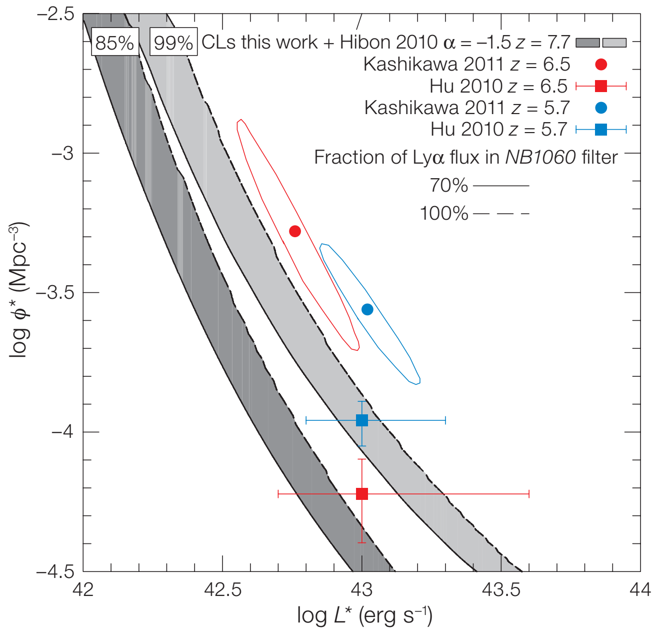


Figure 3. Parameters of the $z = 7.7$ luminosity function excluded at 85% and 99% confidence levels from our data. We report the best-fit LF parameters at $z = 5.7$ (blue) and $z = 6.5$ (red) from Kashikawa et al. (2011) (as filled circles) and from Hu et al. (2010) (filled squares with error bars). The ellipses correspond to the 3σ confidence levels. The plain (dashed) black lines correspond to the 85% and 99% confidence levels assuming a conversion factor of 70% (100%) between the *NB1060* and Lyα fluxes.

ing to the Lyα line falling in the *NB1060* filter, the *Y-NB1060* colour must be greater than 2 mag. To secure the presence of an emission line in the *NB1060* filter, we further require a 1σ narrowband excess over the flux measured in the *J*-band. Finally, we restrict the analysis to sources having a signal-to-noise ratio greater than five in the *NB1060* final images and greater than two in image stacks corresponding to different observing epochs. The corresponding colour criteria used for the selection of candidates differ among the three fields depending on the depth of the optical images available in each of them.

After a rigorous inspection of potential candidates, we eventually concluded that we do not detect any LAE candidates down to a *NB1060* 5σ magnitude of ~ 25.9 to 26.1.

## Constraints on the $z = 7.7$ Lyα LF

The comoving volume sampled by our images corresponds to a grand total of ~ $2.4 \times 10^4$ Mpc$^3$ for the three fields. To constrain the LF of $z = 7.7$ LAEs and compare our results with others, we make use of the Schechter formalism in which the number of galaxies in a given luminosity bin is described by a function with three parameters: a characteristic luminosity $L^*$, a volume density normalisation factor $\phi^*$ and α, the faint-end slope, characterising how steeply the LF increases at low luminosities. From a Poisson distribution, one can easily compute single-sided confidence levels (CL) for the upper limits of the expected number of objects that correspond to a measured number of objects. By example, in our situation of zero detection, the 99.99% CL corresponds to upper limits of the mean number of objects of 10.36. Therefore, with zero detection and assuming pure Poisson statistics, one can exclude, at a given confidence level, the LF parameters that would yield an expected number of objects with our survey parameters.

However, considering the somewhat limited area covered by our observations, we need to consider the effects of cosmic variance in our statistical analysis. Because it fits the SDSS data well (Yang & Saslaw, 2011), we chose to adopt the negative binomial distribution (NBD) as an *ad hoc* representation of the probability density function of low galaxy number counts. The NBD can be conveniently expressed as a Poisson random variable whose mean population parameter is itself random and distributed as a Gamma distribution of variance equal to the relative cosmic variance.

We report in Figure 3 the parameters $L^*$ and $\phi^*$ excluded at 85% and 99% CL together with the best-fit parameters of the LAE LF at redshifts 5.7 and 6.5 from various sources. The faint-end slope α is fixed at α = –1.5. We report the upper exclusion zones derived from the absence of detections in the HAWK-I observations only (this work) combined with the null spectroscopic confirmation of the five brightest $z = 7.7$ LAE candidates presented in Hibon et al. (2010).

The various LF parameters reported in the literature at redshifts 5.7 and 6.5 present some significant differences. Ouchi et al. (2010) and Kashikawa et al. (2011) convincingly claim that the evolution, mostly in luminosity, of the $z = 6.5$ LF from the lower redshift LFs at $z = 3.1$ and $z = 5.7$ is a signature of re-ionisation, due to a neutral hydrogen fraction $x_{HI}$ of

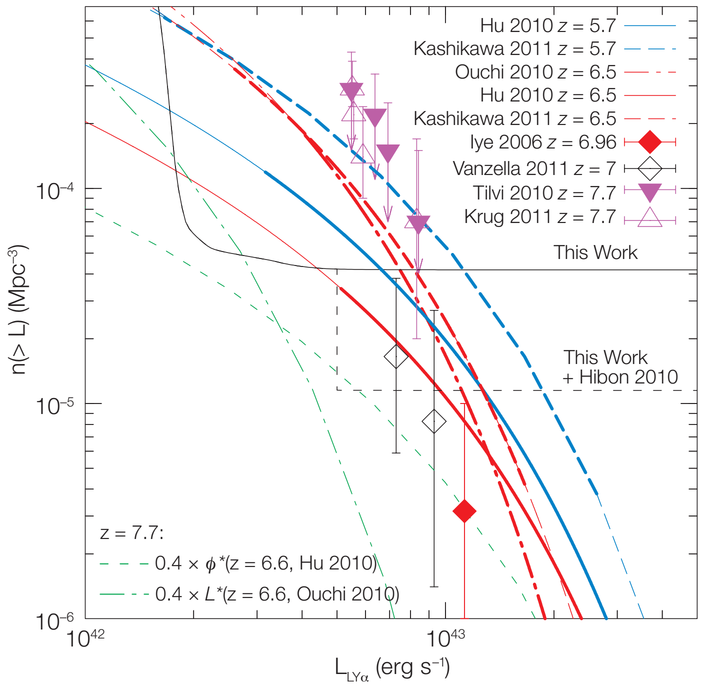


Figure 4. Cumulative Lyα luminosity functions. The blue lines show the cumulative LFs at $z$ = 5.7 and the red lines at $z$ = 6.5 from Hu et al. (2010) (as plain lines) and from Kashikawa et al. (2011) (as dotted lines). The red dotted–dashed line corresponds to the LF at $z$ = 6.5 from Ouchi et al. (2010). The transitions to thin lines indicate the range of the luminosities probed by the observations. The plain line and the dotted black line delimit the parameter space probed by our observations. The green dotted and dotted–dashed lines correspond to two scenarios for the evolution of the LAE LF between $z$ = 6.5 and 7.7. The red filled diamond and the black open diamonds correspond to the spectroscopic confirmation of LAEs at $z$ ~ 7 from Iye et al. (2006) and Vanzella et al. (2011), respectively. The magenta downward-pointing filled triangles are the photometric candidates at $z$ = 7.7 from Tilvi et al. (2010) and the open triangles for the candidates from Krug et al. (2011).

the order of 20% at $z$ = 6.5. Conversely, the evolution of the LF parameters between the same two redshifts deduced by Hu et al. (2010) is mostly in density; accordingly, they do not infer a signature of re-ionisation. How useful are our results in this context?

From Figure 3, we infer that we can safely exclude a scenario with no evolution of the LF parameters at $z$ = 7.7 at more than 99% CL from the Kashikawa et al. (2011) values at $z$ = 6.5. With this LF, we should have found ~ 12 LAEs on average in the three HAWK-I fields. The LF parameters of Hu et al. (2010) would predict ~ 2.5 LAEs at $z$ = 6.5 and can be similarly excluded at more than 90% CL when including the null spectroscopic confirmation of the brightest LAE candidates of Hibon et al. (2010). Our results therefore clearly show that the $z$ = 7.7 LAE LF does evolve from the lower redshifts, but in the absence of concordance between the data at lower redshifts, it is difficult to ascribe this evolution to the galaxy properties or to re-ionisation.

## Two scenarios for the LF evolution

To assess what the consequences of our results might be, we consider two phenomenological scenarios for the evolution of the LAE LF between redshifts 6.5 and 7.7, either in density or in luminosity. We report these two scenarios in Figure 4 and compare them to cumulative Lyα luminosity functions from Hu et al. (2010) and Kashikawa et al. (2011), assuming a faint-end slope fixed at $\alpha$ = -1.5. We also show the parameter space probed by the HAWK-I observations (this work) and the null spectroscopic confirmation of Hibon et al. (2010). In the first scenario, we consider a ~ 60% evolution in density from the $z$ = 6.5 datapoint of Hu et al. (2010). Such an evolution is well reproduced by some models combining the evolution of large-scale structures and of the intrinsic galaxies properties. However, the ultraviolet LF of high-redshift LBGs evolves mainly in luminosity, and such a density evolution for LAEs should therefore be treated with caution. As can be seen in Figures 3 and 4, this scenario would fit most of the observational data available up to redshift 7. The main conclusion from this test case is that to be consistent with our results, it does not require invoking a change in the Lyα IGM transmission and therefore a change in the neutral hydrogen fraction of the IGM. In the second scenario, conversely, we consider a 60% change in luminosity from the $z$ = 6.5 LF of Ouchi et al. (2010). This scenario clearly requires, by construction, a significant quenching of the IGM Lyα transmission. Although strongly model-dependent, a high neutral hydrogen fraction of the IGM (e.g., $x_{HI}$ ~ 60%) would then be required.

In conclusion, our results indicate a significant evolution of the LAE luminosity function at z = 7.7 from lower redshifts. However, we cannot safely decide on whether we are “seeing” signatures of re-ionisation in our results, as this depends on which assumptions we use for the LFs at lower redshifts.

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