A high space density of luminous Lyα emitters at z~6.5

Micaela Bagley, Claudia Scarlata, Alaina Henry and the WISP team
Spectropolarimetry of LAB1

Melanie Beck, Claudia Scarlata, Matthew Hayes, Mark Dijkstra
MOS spectroscopy from FORS2 on ESO-VLT

HWP position angles: 0°, 22.5°, 45°, 67.5°

18,000 sec per HWP

Spatial and wavelength distribution of total intensity Lyα spectrum: 77 co-added spectra smoothed by a Gaussian with FWHM = 0''.5.
Spatial bins 2-3"
Integrated over 4965-5000 Å
Low polarization in regions of high Lyα SB
Increasing polarization in regions of low Lyα SB

Black points from Hayes et al. 2011
MOS spectroscopy from FORS2 on ESO-VLT

HWP position angles: 0°, 22.5°, 45°, 67.5°

18,000s per HWP

Wavelength dependency of Lyα polarization

In bins B–D: low polarization in the core of the Lyα emission and higher polarization toward the wings of the line profile.
Polarization increases with impact parameter.

Polarization increases redward because redder Ly$\alpha$ photons appear farther from resonance in the frame of the gas and scatter less.

“Fingerprint of an outflow”

Large polarization in the red wing can easily be explained with a weak outflowing shell model.

Dijkstra & Loeb (2008)
• Regions of high Lyα SB not strongly polarized

• Spectrally integrated polarization rises at larger radii from the bright central region out to ~15 kpc

• Increasing polarization redward of the line core suggestive of expanding envelope of gas

• Modeling of polarization should include observational slits/conditions
A high space density of luminous Lyα emitters at z~6.5

Micaela Bagley, Claudia Scarlata, Alaina Henry and the WISP team
The progression of the reionization history of the Universe depends on various ingredients related to the physical properties of the first sources.

Number densities, clustering, ionizing power and the fraction of ionizing radiation that is able to escape from the ISM/CGM

\[ \dot{n}_{ion}(z) = f_{esc} \xi_{ion} \rho_{UV} \]

Evolving cosmic ionization rate
What regulates the reionization history

Strongly LyC emitting galaxies (f_{esc} \sim 15-20\%) are needed to reproduce tau — integrating the LF to 0.001L_*

\[ \dot{n}_{ion}(z) = f_{esc} \xi_{ion} \rho_{UV} \]

The number density of galaxies is likely the best constrained quantity that enters the calculation of the cosmic ionization rate.

Levermore et al. (2017)
The reionization history can be constrained “directly” from

- absorption line studies along the line of sight of high redshift QSOs
- the evolution of Lyα emitter number density and the fraction of Lyα emitters among LBGs
There is reasonable agreement that the number of LAEs remains relatively constant between $z$ of 3 and 5. The evolution above $z>5.5$ is still rather uncertain.

Some differences could be resolved with observational effects (e.g., different spectroscopic completeness and/or contamination to narrow band searches)
A different possibility could reflect the patchy nature of the reionization process.

Luminosity and clustering of galaxies combine to produce large ionized bubbles (on scales of a few Mpcs) that could allow Ly$\alpha$ photons to redshift out of resonance before encountering the IGM.

$\Rightarrow$ one may expect bright Ly$\alpha$ emitters to be visible to earlier times.

Zheng et al. 2011
Why move into space?

From the ground — spectroscopic confirmation is challenging (e.g., Alyssa’s completeness analysis as a function of lambda)

From space, continuous redshift coverage from z>6

Low stable background and higher resolution help with faint / compact sources
The WFC3 Infrared Spectroscopic Parallel Survey

large HST (~2000 orbits) pure parallel program surveying the sky both in spectroscopy (slitless) and imaging.

Many independent fields (> 400, ~1600sq. arcmin.) overcoming cosmic variance

Deep survey

imaging

IR \( (J_{110}, H_{160}) \) + UVIS \( (V_{606}, I_{814}) \)

Average \( 1\sigma \) depth in UVIS = 27.6 AB mag

spectroscopy

G102: 0.8 - 1.1 \( \mu m \) (R\~210)
G141: 1.07 - 1.7 \( \mu m \) (R\~130)
We choose the 48 deepest WISP fields, covering \( \sim 160 \) arcmin\(^2\).
WISP data

Direct image

Dispersed image

Zero order image

Emission lines

Screen capture of ¼ of the entire FOV
Galaxy selection

We look at all galaxies that in the WISP catalog had a single emission line.

Large library of synthetic templates with $0.1 \leq z \leq 8.5$, and emission lines. We varied three parameters: (1) the redshift range (2) the level of flux allowed in I814, and (3) the colors

- a single emission line at $\lambda_{\text{obs}} \leq 1.05 \mu\text{m}$; detected at 5σ in J$_{110}$

- with colors consistent with $z \geq 6$ galaxies

- undetected at the 1σ level in all available optical filter
Contamination

Photometric uncertainties and real red colors (e.g., strong Balmer break) can cause contamination to the sample of single-line Lyα emitters.

Contaminants in the sample are restricted to very narrow redshift ranges, corresponding to Lyα in

\[0.85 \leq \lambda_{\text{obs}} \leq 1.05\mu\text{m}\]

<table>
<thead>
<tr>
<th>Emission Line</th>
<th>Redshift Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hα</td>
<td>0.3 \leq z \leq 0.6</td>
</tr>
<tr>
<td>[O III]</td>
<td>0.7 \leq z \leq 1.1</td>
</tr>
<tr>
<td>[O II]</td>
<td>1.3 \leq z \leq 1.6</td>
</tr>
</tbody>
</table>
We can reject the vast majority plausible low-z contaminants.

**Hα-emitters:**
All detected in the UVIS filters at the depth of the survey.

**[OIII]-emitters:**
~2% of galaxies with [OIII] fluxes similar to those of the LAE candidates have Hα fluxes ≤ the WISP sensitivity limit.

**[OII]-emitters:**
We should detect [OIII] in the redder grism. All WISP [OII]-emitters with fluxes similar to the LAEs have [OIII] > the sensitivity limit.
WISP302

$z = 6.44$

$f_{\text{Ly}\alpha} = 9.9 \times 10^{-17} \text{ erg/s/cm}^2$

$L_{\text{Ly}\alpha} = 4.67 \times 10^{43} \text{ erg/s}$

$EW = 798 \pm 531 \text{ A}$

WISP368

$z = 6.38$

$f_{\text{Ly}\alpha} = 10.2 \times 10^{-17} \text{ erg/s/cm}^2$

$L_{\text{Ly}\alpha} = 4.71 \times 10^{43} \text{ erg/s}$

$EW > 1172 \text{ A}$

The emission line contributes $\approx 70\%$ to the $J_{110}$ flux density

The WISP LAEs are among the brightest discovered at $z \approx 6.5$. 
Number density consistent with Mathee’s et al. (2015)

who report no evolution at the bright end from $z = 5.7$ to $z = 6.5$

$\Rightarrow$ the brightest galaxies already reside in ionized bubbles by $z \sim 6.5$.

Such bubbles would enhance the field-to-field variations in the observed number counts of LAEs and may also partially explain the differences at the bright end between the LFs.
We find no LAEs at $7.0 < z < 7.63$
At the WISP $3\sigma$ median depth, we would expect to detect 3.1 LAEs at $z>7$
based on the bright galaxies we see at $z\sim6.6$

→ The probability that this $z=6.6$ LF also applies at $z>7$ is 4.5%.
Results from 100 mock light cones from Garel et al. (2015) — combine semi-analytic model with numerical simulations of Lyα radiation transfer through shells (Verhamme’s models), neglecting the IGM.

Light blue: intrinsic Lyα emission
Light grey: Lyα attenuated by a shell

The number density of bright LAEs is consistent with predictions from mock catalogs that use the intrinsic Lyα emission (i.e., \( f_{\text{esc}} = 100\% \)).

**Statistically** - Lyα photons:

- **able to escape the galaxies’ ISM**
- **are not substantially attenuated by the surrounding IGM**.
Given the rest-frame UV continuum it seems that WISP 302 has a Lyα escape fraction of 90 to 100%. Only models with a very young age and low metallicity produce an OBS/INT ratio <1.

⇒ no ISM attenuation

The ratio of OBS/INT Lyα ~ 90-100% also suggests no substantial IGM attenuation

— locally: galaxies with the highest Lyα fesc are characterized by emission line profiles with substantial flux on the blue side and centroid close to systemic velocity (see GP talks).

— The neutral IGM at z ~6.5 would attenuate this blue emission considerably, causing OBS/INT Lyα <100%
Given the rest-frame UV continuum it seems that WISP 302 has a Lyα escape fraction of 90 to 100%. Only models with a very young age and low metallicity produce an OBS/INT ratio <1.

⇒ no ISM or IGM attenuation

Lyα can be transferred if \( \tau_{\text{IGM}} < 1 \)
⇒ Uniform ionized IGM? unlikely
⇒ \( R_{\text{bubble}} \sim 1\text{Mpc} \)

What do we need to create this bubble?
The minimum radius for Lyα to escape is \( \sim 1.3 \text{pMpc} \) \( (\tau_{\text{IGM}} < 1, \text{Miralda Escude’ 1998}) \)

We followed Cen & Haiman (2000) to compute the maximum radius ionized over the course of WISP302 ‘s life time

\[
R_{\text{max}} = \left( \frac{3 \ N_{\text{ion}}}{4 \ \pi \ \langle n_{H} \rangle} \right)^{1/3}
\]

\( N_{\text{ion}} \) depends on the escape fraction and the intrinsic production rate of LyC photons.

Even assuming an escape fraction of 100% (obviously wrong) we still would get a radius of only half of the required one…

\( \rightarrow \) clearly the bright Lyα emitter we observe cannot be responsible of its own bubble
1) A population of very numerous small galaxies

if \( \alpha = -1.5 \) ==> we need to integrate down to 0.001 \( L^* \)

if \( \alpha > \sim 2 \) (e.g., Dressler et al. 2015) ==> we need only integrate down to 0.04 - 0.1 \( L^* \).

2) A very bright QSO outside of the field of view

For the same UV luminosity, QSOs produce an x10 more ionizing photons and the LyC escape fraction is likely \( \sim 100\% \).

Required H \( \sim 22 \) AB (not crazy)
With the full WISP we will have → 182 deep fields, x 4 in area (up to ~640 arcmin²)
Probing a volume at $6 \leq z \leq 7$ of $\sim 2.3 \times 10^6$ Mpc³
Future planned space missions (Euclid & WFIRST) – require millions of redshifts in order to probe dark energy using Baryonic Acoustic Oscillation.

Future long term: Euclid / WFIRST

ACS  WFC3  JWST/NIRCAM

Exact area/strategy depends on the requirements of the # of galaxies
WISP will have \(\sim 1000 \text{ arcmin}^2\) with continuous 0.8—1.6\(\mu\text{m}\) spectral coverage providing access to gold standard indicators for star formation / dust absorption / gas metal content / stellar ages during the peak of the cosmic star—formation history.

New release coming soon!
Conclusions

Polarization of Lyα blob:

Spectrally integrated polarization rises at large radii out to ~15 kpc
Large polarization redward of the line core suggests expanding envelope
More modeling is needed

z~6 Lyα emitters:

two bright galaxies in 160sq. arcmin.
100% escape of Lyα photons in the brightest sources
reionization likely proceeds highly inhomogeneously
significant evolution at the bright end between z~6.6 and 7.3

WISP: pathfinder future space missions (Euclid, WFIRST)