A deep imaging and spectroscopic investigation of a reionized bubble at z~7

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Timeline and sources of HI Reionization

*Decline of Ly$\alpha$ visibility in star-forming galaxies key probe of late reionization (e.g. Stark+10, Fontana+10, Pentericci+11,+14, Schenker+12)

*Reionization timeline can be explained by the evolution of UV luminosity density from star-forming galaxies (e.g. Bouwens+15, Robertson+15).

Patchy topology favoured (Treu+12, Pentericci+14)
A space oddity at z=7: three close-by strong LAEs

In the overall paucity of Lyα lines: one line of sight with twin bright emitters among the 8 l.o.s. investigated in Pentericci+14 (see also Pentericci +18).

The BDF4 field (Lehnert&Bremer 03) hosts three close-by EW~50-60AA emitters.

Additional sources required to Reionize the region? (e.g. Dayal+09)
A space oddity at $z=7$: three close-by strong LAEs

$Z=7.109$
$EW=50\text{AA}$
$\text{FWHM}=200 \text{ km/s}$

$Z=7.008$
$EW=50\text{AA}$
$\text{FWHM}=240 \text{ km/s}$

$Z=7.008$
$EW=64\text{AA}$
$\text{FWHM}=240 \text{ km/s}$
A space oddity at z=7: three close-by strong LAEs

Only ~90kpc physical separation, very same redshift: a galaxy pair in the reionization epoch at 1.9 pMpc projected distance from the other LAE BDF3299
An overdensity of z~7 LBGs around the three LAEs

Observed = 8 objects in two pointings. Expected $N_{\text{exp}} \sim 1.8-2.9$ objects (cosmic variance: $0.5N_{\text{exp}}$).

The BDF field is 3-4x overdense wrt average: consistent with a positive relation between line visibility and galaxy density as in inside-out reionization scenarios. (e.g. McQuinn+ 07, Wyithe&Loeb 07, Dayal+ 09). No similar clustering around bright z~7 LBGs in CANDELS GS.

MC+ ApJL, 2016a
Connection between reionization and overdensities

Comparison with SPH model (Hutter+14,+15).

✓ Relation between density and HI fraction
✓ Clustered LAEs live in overdense regions with low HI
✓ BDF analogs are reionized, overdense bubbles
Spectroscopic follow-up of the full z~7 sample

33 hrs FORS2@VLT, (program 099.A-0671 P.I. MC)

600z+23(OG590) grism (resolution R=1390), with slits 1" wide and a length in the range 6-12"

Observed 14 robust S/N(Y105)>5 z~7 candidates, plus z~6 fillers and lower quality LBGs

Plus FORS2 data on the two LAEs BDF521 and BDF3299 and another bright HAWK-I-selected candidate from programme 181.A-0717
No Lyα from any of the faint galaxies

3 out of 5 “bright” LBGs have Lyα

No detections from faint (Y>26.7) sources

<table>
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<tr>
<th>Sample</th>
<th>Total</th>
<th>Bright</th>
<th>Faint</th>
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<tr>
<td>Observed</td>
<td>17</td>
<td>5</td>
<td>12</td>
</tr>
<tr>
<td>Detected in Lyα</td>
<td>3</td>
<td>3</td>
<td>0</td>
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Comparing number of detected lines to number of expected detections under different hypothesis:
- peaked (“Flat” at z=7) or wide (“P(z,Y)”) redshift distribution
- z=7 (low) or z=6 (high) line transmission through the IGM

Stacked spectrum
No Ly\(\alpha\) from any of the faint galaxies

3 out of 5 “bright” LBGs have Ly\(\alpha\)

No detections from faint (Y>26.7) sources

Low prob. of 3 bright (M_UV<-20.25) LAEs (less are expected)
\(\Rightarrow\) High visibility, more consistent with a z\sim6 reionized Universe

Stacked spectrum

MC+ ApJL, 2018
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3 out of 5 “bright” LBGs have Lyα

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PDF(z)  | Lyα visibility | $P_{(tot = 3)}$ | $P_{(bright = 3)}$ | $P_{(faint = 0)}$ | $< N_{tot} >$ | $< N_{bright} >$ | $< N_{faint} >$ |
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<tr>
<td>Flat</td>
<td>z=7</td>
<td>0.21</td>
<td>0.009</td>
<td>0.17</td>
<td>2.1</td>
<td>0.7</td>
<td>1.4</td>
</tr>
<tr>
<td>P(z,Y)</td>
<td>z=7</td>
<td>0.18</td>
<td>0.009</td>
<td>0.22</td>
<td>1.9</td>
<td>0.7</td>
<td>1.2</td>
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<td>Flat</td>
<td>z=6</td>
<td>0.08</td>
<td>0.035</td>
<td>0.002</td>
<td>5.5</td>
<td>1.2</td>
<td>4.3</td>
</tr>
<tr>
<td>P(z,Y)</td>
<td>z=6</td>
<td>0.11</td>
<td>0.036</td>
<td>0.004</td>
<td>5.0</td>
<td>1.2</td>
<td>3.8</td>
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Low prob. of 0 faint (M_UV>-20.25) LAEs (more are expected) → Low visibility, more consistent with z~7 half-neutral Universe

Stacked spectrum

MC+ ApJL, 2018
Possible scenarios

- Bright galaxies are in a reionized “bubble” but faint galaxies are outside.

- Bubbles are created by the bright galaxies alone (SFR and/or AGN), or by bright galaxies+ objects beyond the current BDF detection limit ($M_{UV}$>-19, e.g. Vanzella+17a,b).

- Ly$\alpha$ from bright galaxies is boosted by velocity offsets and/or enhanced photon production (Mason+2018, Stark+2017).

- Bright and faint galaxies are all members of the reionized “bubble” but some mechanisms decrease Ly$\alpha$ escape from faint galaxies.

- Accelerated evolution of overdensity members: bright galaxies are young with high SFR, faint LBGs are more evolved and dustier.

- Recombination of neutral hydrogen in the regions close to overdensity members, velocity shifts (higher in massive galaxies) are needed to make the line visible to us.

MC+ ApJL, 2018
Are bright galaxies enough?

We estimate the **size of the bubble** (e.g. Madau 1999) **created by each galaxy** for all SED-fitting models compatible (68%c.l.) with the observed photometry.

Constant SFR, BPASS V2.0 libraries, Calzetti extinction. **Escape fraction of UV ionizing photons** ($f_{\text{esc}}$) varied from 0 to 1.

Compare to size needed to have Ly$\alpha$ redshifted to us (Loeb et al. 2005)
When summing the two contributions the BDF521-BDF2195 pair can create a large enough bubble with $f_{\text{esc}} > 10\text{-}15\%$ and moderate SFRs over $> 400\text{Myr}$ lifetime.

Adding the contribution of 220 km/s shifts $f_{\text{esc}} < 10\%$ can do the job.

But no way for BDF3299 which is $>2\ \text{pMpc}$ distance from the pair.

*MC+ ApJL, 2018*
What about AGN?

$\text{Ly} \alpha / NV > \sim 8-10$ on single spectra

$\text{Ly} \alpha / NV > 17$ on stacked spectrum

Limits not enough to rule out AGN. Not to mention past AGN activity...

MC+ ApJL, 2018
Waiting for JWST

JWST-NIRSPEC can easily detect optical lines, and look for other faint lines in the UV range. We will be able to:

1. Assess whether faint candidates are members of the localized overdensity at $z \sim 7.0-7.1$ as the bright ones.

2. Perform accurate measurements of SFR, extinction and age ($H\alpha$ luminosity, $H\alpha/H\beta$ and $H\alpha$/UV ratios) to constrain re-ionization capabilities.

3. Measure velocity shifts between Ly$\alpha$ and UV/optical lines.

4. Probe signatures of a high escape fraction (e.g. Zackrisson+13, Verhamme+15, de Barros+16, Chisholm+18 etc).

5. Probe signatures of AGN or of hard ionizing stellar spectra (e.g. Stark+17, Mainali+17, Senchyna+17, Schaerer+18).

6. Confirm a low neutral fraction looking for blue wings in high-resolution Ly$\alpha$ spectra (e.g. Hu+16).
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Deep X-SHOOTER observations coming soon!

A total of 42 hours exposure time approved for Period 103. Goal: constraining the physical properties of these unique objects through deep UV rest-frame spectroscopy of the CIV, HeII, OIII], CIII] lines.
The future: synergies to map early reionized regions

1) **Euclid Deep Fields**: 40 sq. deg. multi-wavelength at CANDELS depth (NIR~26).

   *Selection, LF and morphology of L~L* Lyman Break galaxies in the reionization epoch.*

2) **VLT-MOONS**

   (500 arcmin² FoV, R>4000, λ=0.65-1.8µm)

   *Spectroscopic follow-up of L~L* LBGs, Lyα LF.*

3) **JWST**

   *Selection, LF, morphology and spectroscopy of faint LBGs around L* LAEs.*

4) **ELT/TMT/GMT**

   *Ultra-deep AO-assisted spectroscopy, morphology and dynamics of faint and bright LBGs and LAEs.*

Emulation of EDF-Fornax, EC/OU-MER
The future: synergies to map early reionized regions

5) SKA

Connecting galaxy density field and 21cm signal to map reionization topology (e.g. Hutter+17,+18)
Three close-by z\sim7 LAEs in the BDF field embedded in an overdensity of faint LBGs. They are all L\simL* galaxies.

Two LAEs form a pair at \sim90 kpc distance.

Ly\alpha fraction much higher than average at z\sim7: patchy scenario (see Pentericci+14) likely due to clustering.

Consistent with the presence of overlapping reionized “bubbles” of \sim5Mpc radius.

Puzzling lack of Ly\alpha from faint companions: low Ly\alpha escape from faint galaxies?

The pair BDF521-BDF2195 can reionize their surroundings with “reasonable” f_{\text{esc}} \sim5-20%.

BDF3299 would require other (ultra-faint?) sources, or AGN (but Ly\alpha/NV\gg10).

Ideal target for JWST to discriminate among various scenarios.

Hot topic for the future: synergy among future telescopes will allow to select and investigate many regions like the BDF.