Measuring the Evolution of Reionization w/ Big-Glass Observations of Lyα emission

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Featuring work led by UT graduate students

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Based on Astro2020 Science White Paper (https://arxiv.org/pdf/1903.04518) by:
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How rapidly does reionization end?

Understanding how reionization ends can tell us what drives it.

All galaxies have 10-20% escape fractions.

Brighter (>0.1L*) galaxies drive reionization.

The lowest-mass galaxies have the highest escape fractions.

The faintest (<0.001L*) galaxies drive reionization.
What is the ionized fraction at z~7-8?

- Lyα should be a sensitive tracer of reionization (e.g., Miralda-Escude+98, Malhotra & Rhoads 04, 06; Furlanetto+06; Dijkstra+07).

- It is relatively “abundant” at z=6, just after the end of reionization, and is resonantly scattered by HI.

- A patchy IGM should be directly traceable by the patchiness of Lya emission.

\[ X_{HI} = 0.7 \]
\[ X_{HI} = 0.5 \]
\[ X_{HI} = 0.3 \]

McQuinn+2007
Is Lyman-alpha indicating a substantially neutral IGM?

- This has led to a booming industry of attempted Ly\(\alpha\) measurements at \(z > 6.5\), with some notable successes (e.g., Shibuya+12, Finkelstein+13, Rhoads+13, Oesch+15, Zitrin+15, Roberts-Borsani+16, Song+16, Stark+16, Hoag+17, LaPorte+17).

\(z=7.17\)

\(z=7.51\)

\(z=7.73\)

\(z=8.68\)
What is the ionized fraction at $z \sim 7-8$?

- In spite of some detections (e.g., Shibuya+12, Finkelstein+13, Oesch+15, Zitrin+15, Song+16, Stark+16, Hoag+17, LaPorte+17, Hu+18), the majority of $z>7$ galaxies go undetected with spectroscopic followup.

- How high of a neutral fraction is needed?
  - The most recent studies infer $X_{HI} = 60-90\%$ at $z=7-8$ (Mason+18,19; Hoag+19).

- However, converting observed spectra to constraints on the neutral fraction has lots of assumptions and potential for systematic uncertainties, including:
  - Incomplete spectral coverage of the full $P(z)$; copious telluric emission lines.
  - Limited spectroscopic depth
  - Small areas covered
In Intae Jung’s thesis work, we used data taken over 18 nights from Keck with DEIMOS and MOSFIRE to try to overcome some of these systematics, specifically:

- **Depth:** Our MOSFIRE integrations range from 5-20 hours.
- **Sample selection:** Significant effort to improve the photo-z’s (and minimize sample contamination) of the observed galaxies.
- **Wavelength:** ~20 of our sources are covered by both DEIMOS and MOSFIRE.

72 galaxies observed w/ MOSFIRE at \( t > 5 \text{ hr} \)
Nine $z > 7$ Ly$\alpha$ lines detected at $>4\sigma$ @ $z_{\text{Ly}\alpha}=7.1$-$7.9$ (five at $>5\sigma$ @ $z=7.1$-$7.6$)

**$EW_0 \sim 20$ - 200 Å** (see also Larson+18)

Significant asymmetry is seen when S/N > 10
We use our observations to model the Ly$\alpha$ equivalent width (EW) distribution, accounting for all sources of incompleteness and uncertainty by implementing via MCMC (Jung+18, 19ab). We constrain the characteristic scale-length of this distribution, predicting for a given value the number of lines we should detect at a given S/N in our data.
Implications: Lyα is very detectable in this epoch. Our measured value of $W_0 \sim 30 \text{ Å}$ at $z \sim 7.5$ implies a neutral fraction which is non-zero, but perhaps $< 50\%$.

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We constrain the characteristic scale-length of this distribution, predicting for a given value the number of lines we should detect at a given S/N in our data.
TRYING TO PUSH TO Z=9

- We (PI Rebecca Larson) have been leading Keck/MOSFIRE followup of a larger sample of bright z~9-10 galaxies (SF+19b, in prep).

- We have observed ~10 galaxies at t=5-10 hr depth in the J-band, which covers Lyα at z~8.5-10.1.

- After a ***lot*** of hard work, accounting for drift along the slit, and differing slit positions between observations, we have a few potential detections.

- How to best confirm these? ALMA can help, though many of these are in the north. Big glass would be great!
WHAT REMAINING PROBLEMS ARE THERE?

• Combing back to z~7-8, our sample is still small - an effective 10 nights of integration with Keck, and we were only able to observe ~20 galaxies to >10 hr.

• Most of these are bright (J < 26.5)

• The MOSFIRE FOV is small.

• Large areas (1 deg$^2$+) need to be observed to overcome CV, and probe multiple ionized bubbles.

• The need: a **wider field and larger aperture**.
Scales of reionization

Figure credit: Ocvirk+2019
WHAT WILL PROVIDE THE GALAXY SAMPLE?

**WFIRST**

Predictions assume smoothly evolving Schechter UV LF (Finkelstein 16), and limiting magnitudes = 26.5 for HLS (except for z=7, which is limited by z’_{LSST}=26.2 depth), with empirically derived (from HST) magnitude-dependent completeness applied.

GO deg^2 survey is a roughly 500 hr survey observing one square degree to m~29.

<table>
<thead>
<tr>
<th>z</th>
<th>Expected # (HLS)</th>
<th>Expected # (deg^2 GO)</th>
<th>m~29 number per 20’ FOV</th>
</tr>
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<tbody>
<tr>
<td>6</td>
<td>$\sim$3,300,000</td>
<td>$\sim$21,000</td>
<td>$\sim$2300</td>
</tr>
<tr>
<td>7</td>
<td>$\sim$530,000</td>
<td>$\sim$9200</td>
<td>$\sim$1000</td>
</tr>
<tr>
<td>8</td>
<td>$\sim$280,000</td>
<td>$\sim$4000</td>
<td>$\sim$450</td>
</tr>
<tr>
<td>9</td>
<td>$\sim$75,000</td>
<td>$\sim$1700</td>
<td>$\sim$200</td>
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<tr>
<td>10</td>
<td>$\sim$19,000</td>
<td>$\sim$700</td>
<td>$\sim$80</td>
</tr>
</tbody>
</table>
Zoom in on a 1’x1’ image from the CANDELS Deep survey, showing the positions of $5.5 < z < 6.8$ (red) and $z > 6.8$ (magenta) galaxies.
Simulated GMT observations of WFIRST deep GO pointings.

30 hr should reach limiting emission line fluxes of ~2-3 x 10^{-19} cgs.

Significant science can also be done with other rest-UV lines, primarily CIII] 1907,1909, which probes the systemic redshift, and can constrain the metallicity and ionizing properties of the stellar populations.
WHY NOT JWST?

**Immense Gain in Multiplexing**

The *JWST* NIRSpec FOV is only 3’x3’. The area probed by a single MANIFEST pointing is ~40X larger. The most efficient NIRSpec R~1000 or 2700 configurations net ~60 targets per observation, compared to up to 1000 objects observed per MANIFEST pointing.

**Throughput**

The NIRSPEC throughput begins to decline at $\lambda < 1.2\mu m$.

These two factors combined imply that *JWST* will *not* perform the deep and wide-field spectroscopic surveys necessary for Ly$\alpha$ probes of reionization at z~6-10 (though it will certainly provide guidance for such future studies).
TAKE-HOME POINTS

- Pinning down the detailed evolution of the reionization process places constraints on the nature of the earliest galaxies in the universe.

- Lyman-alpha emission is currently the best diagnostic to measure the neutral fraction (and even in the SKA-era, is very complementary).

- “Heroic” integrations with 10m-class telescopes show that Lyman-alpha is still detectable to z~9, but bigger glass and a wider field-of-view are needed to gain a clear picture of reionization.

- Combining the wide-field galaxy sample from WFIRST with the wide-field spectroscopic capabilities of GMT provide a clear path forward.

See more in our Astro2020 White Paper: https://arxiv.org/pdf/1903.04518