One step toward understanding cosmic re-ionization: Absorption tests with a new QSO we discovered at z=6.6

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Subaru 20th anniversary 19 Nov.
Outline

• Introduction
• Sample: PSO J006+39
• Analysis
• Results
• Summary
Introduction:
Cosmic reionization

Credit: Marcelo Alvarez, Tom Abel, & Ralf Kaehler
Introduction:

Lyman alpha absorption
Introduction:
What we can observe from QSO at $z \sim 6$

Fan et al. 2006

Strong absorption at high $z$

Gunn-Peterson trough

To measure slightly transmitted flux, we need

(i) High-z
(ii) Bright
(iii) High quality spectrum
Sample: (i) High-z
Pan-STARRS1 (ii) Bright

1) $-0.3 < y_{Kron} - y_{psf} < 0.3$
2) $z - y > 2.0$
3) SNR in $y$ band $> 10$
4) $y$ detection in 2+ epochs
5) $i$ and $z$ mag $> 24$
6) Visual check by eyes

Tang et al. 2017, 2019
PSO J006+39
$z_{[CII]} = 6.621 \pm 0.002$
(Mazzucchelli+2017)
$M_{1450} = -25.55$
$M_{SMBH} = 10^8 M_{\odot}$

Our sample
Pan-STARRS QSO
PS1
HSC

Bañados+2016
$M_{1450} = -25.55$

Redshift

$M_{1450}$

5.5 5.9 6.3 6.7 7.1
Sample: Subaru/FOCAS

(iii) High quality spectrum

Spectroscopic follow-up observations with FOCAS

One of 12 candidates

Tang et al. 2017

5 ksec
R~600

27 ksec
R~5500

Observed wavelength (Å)

Flux (10^{-17} ergs cm^{-2} Å^{-1})

z=6.62

Observed
Intrinsic

This work

Observed
Intrinsic

Ly\alpha

N\gamma

O I + Si II

Observed wavelength (Å)
Analysis:
the high-quality spectrum allows us to do

1. Lyman alpha transmission
2. Near zone size (e.g., Fan+2006)
3. Dark gap (e.g., Fan+2006)

Need continuum modeling

Model free

27 ksec
R~5500

z=6.62

Observed
Intrinsic

This work

Observed
Intrinsic

Flux (10^{-17} \text{ergs} \text{ cm}^{-2} \text{ Å}^{-1})

Observed wavelength (Å)

7500 8000 8500 9000 9500 10000 10500
Analysis:

(1) Lyman alpha transmission

- Continuum fitting using \( F_\lambda = F_0 (\lambda/2500 \text{Å})^{\alpha_\lambda} \), 
  \( \alpha_\lambda = -2.94 \pm 0.03 \) (Tang et. al. 2019)

- Ly\( \alpha \) transmission & optical depth at 5.64<z<6.45 
  (bin size=50cMpc, \( \Delta z \sim 0.12 \))
We extended the transmission measurement up to $z \approx 6.5$.

Analysis:

1. Lyman alpha transmission (result)

$$T = \frac{\text{Flux}_{\text{obs}}}{\text{Flux}_{\text{intrinsic}}}$$

Optical depth = $-\ln(T)$

<table>
<thead>
<tr>
<th>Redshift</th>
<th>This work (Lyα)</th>
<th>This work (Lyα lower limit)</th>
<th>This work (Lyβ)</th>
<th>This work (Lyβ lower limit)</th>
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![Graph showing Lyman alpha transmission results]
Analysis: (2) Near zone size

HII bubble of QSO, where Lyα transmission drops to 0.1

Loeb 2006

Willot 2011
Analysis:

(2) Near zone size result

\[
\text{Normalized near zone size} = \text{Near zone size} \times 10^{0.4(27+M1450)/3}
\]
(3) **Dark gaps:** neutral islands along the LOS to QSO

- **Flux**
  - **obs**
  - ***Flux***

Wavelength = neutral island’s redshift/size

- **Lower redshift**
  - **Example**
  - **Example**

- **Higher redshift**
  - **Example**
  - **Example**

**Dark gaps**

- **Example**
  - **Example**

**Flux**

- **Tau=2.5**
- **Tau<2.5**
- **Tau>2.5**
Analysis:

(3) Dark gaps: result

- This work (5.5 < z < 6.0)
- Simulation (5.5 < z < 6.0) - Poschos & Norman 2005
- Simulation (5.7 < z < 6.3)
- This work (5.7 < z < 6.3)
- Gallerano et al. 2006

### Graphical Data

- **Absorber's redshift** vs. **Size of dark gap/absorber (Mpc)**
- **Log width of dark gap (Å)** vs. **Log # of dark gaps**

- **tau > 2.5:**
  - *this work*
  - Fan et al. 2006
  - Fan et al. 2006 (average)
Analysis:

(4) **Dark pixel**: independent from continuum model

- Dark pixel --> Neutral gas (upper limit)
- Bright pixel --> Ionized gas

Number fraction of dark pixels to bright ones

\[ \frac{N_{\text{dark}}}{N_{\text{Bright}}} \sim \text{upper limit on } <x_{\text{HI}} > \]
Analysis:

(4) Dark pixel: result

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<tr>
<th>Redshift</th>
<th>Lyα (This work)</th>
<th>Lyα (McGreer11)</th>
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<tbody>
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<td>5.4</td>
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<td>6.6</td>
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Threshold=0

Threshold=2σ

3.3 pMpc bin

This work
Summary

• Lyα transmission: $z \sim 6.3$ (literature)  
  $\rightarrow z \sim 6.5$ (this work)
• Dark gap distribution $z \sim 5.5$ (literature)  
  $\rightarrow z \sim 6.0$ (this work)
• (From dark pixel) upper limit of $<X_{\text{HI}}>$  
  $\sim 0.6$ at $z < 5.8$, $\sim 0.8$ at $z > 5.8$
• All the four analysis support higher neutral fractions at higher redshift
• More discoveries/observations of bright high-z QSO are necessary for a comprehensive understanding of cosmic reionization history