Lessons from Helium Reionization (?)

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Thanks to F. Davies, K. Dixon, A. Mesinger, and S. P. Oh
Outline

- The Reionization Eras: Introduction
  - Basic theoretical models
- HeII Reionization as an analog?
  - Photon-counting
  - Maintaining reionization
  - Fluctuations in the Lyα forest
  - Average optical depth
  - Temperature evolution as a probe
  - Dynamical effects
- Conclusions
The Reionization Process I

- **Limit #1:** “Photon counting”

- **Ionizing photons escape each source, and form ionized bubbles in IGM**

- **Bubbles grow and merge as more sources appear**

Mesinger & Furlanetto (2007)
When Was Helium Reionization? (I)

- **Ingredients:** source luminosity function
- **Quasars produce enough ionizing photons at** $z \sim 3.6$

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Furlanetto & Oh (2008)
H I Reionization: The Movie
Bubble Sizes: H I Reionization

- **Bubbles grow throughout reionization**
- **Driven by source clustering: massive halos, big bubbles**
- **LOTS of sources per bubble**
- **Quasars produce enough ionizing photons at** $z \approx 3.6$
- **Precise timing depends on recombination rate**
- **Parameterized crudely by** “clumping factor:” enhancement relative to uniform IGM from clumping: rate $\sim n^2$

Furlanetto & Oh (2008)
The Reionization Process II

- Emission rate > recombination rate

- Most recombinations are inside “Lyman-limit systems”

- Matters once (size of bubble) > (attenuation length)

- Controls post-reionization paths
When Was Helium Reionization? (II)

- **Ingredients**: source luminosity function + clumping

- **Recombinations occur in** (well-measured) Lyman-α forest

- **See Fred Davies’ poster for more details!**

\[
\eta_{\text{thin}} = \frac{N_{\text{HeII}}}{N_{\text{HI}}}
\]

Davies & Furlanetto (in prep)
Reionization Models: The Ingredients

\[ \Gamma x_n \times = \alpha(S, T) C \langle x \rangle \]

- Source luminosity function (at all z)  
  \[ \text{He II} \quad \text{H I} \]
- Mean free path and clumping (Lyman-\(\alpha\) forest)  
  \[ \text{He II} \quad \text{H I} \]
- The details
  - Spectrum  
    \[ \text{He II} \quad \text{H I} \]
  - Temperature  
    \[ \text{He II} \quad \text{H I} \]
  - Geometry of absorbers  
    \[ \text{He II} \quad \text{H I} \]
  - Environments of sources  
    \[ \text{He II} \quad \text{H I} \]

Easy Hard Terrible
He II Reionization: The Movie

Ionized Fraction
Blue: HeII
Red: HeIII

430 Mpc

McQuinn et al. (2008)
Qualitative Differences Between H I and He II Reionization

- Ionization topology is meaningful for H I (driven by clustering)
- H I reionization is “inside-out”
- “Fossil” ionized bubbles important for helium but not hydrogen (Furlanetto, Haiman, & Oh 2008)

Photon Counting Phase: Not much of a help!
The End of Reionization

- Eventually LLSs take over and regulate the end of H I reionization
  - Current estimates: ~2 ionizing photons/atom over age of universe at z=6 imply slow transition (e.g., Bolton & Haehnelt 2007)
  - He II reionization is rapid...
  - ...but also dominated by LLSs!

Recombination Phase: Could be a help!
Fluctuations in the Forest

- Lots of variation!
- Slow evolution at $z<2.7$
- Rapid evolution, and large fluctuations, at $z>2.8$

See also McQuinn (2009)

Fan et al. (2006)
Fluctuations During Hydrogen Reionization

- **He II**: rare, bright sources mean large fluctuations in $\Gamma$
- **H I**: many, many sources!
- **Optical depth of the (uniform) IGM with a reasonable ionizing background**: 
  \[
  \tau_{\text{GP}_{\text{HI}}} \approx \frac{130}{\Gamma_{-13}} \left( \frac{1 + z}{7} \right)^{9/2} \left( \frac{T_0}{10^4 \, \text{K}} \right) \Delta^2
  \]
- **H I**: damping wing

Lidz, Oh, & Furlanetto (2006)

**Forest Fluctuations:**
Not an analog
The Average Optical Depth

- No sharp feature is necessary in HI reionization
- But it will still occur whenever $\Gamma$ changes rapidly

Dixon & Furlanetto (2009)
Furlanetto & Mesinger (2009)
But will there be such a feature anyway?

- **YES for He II, but...**
  - Rapid evolution in luminosity function
  - Structure of forest in relevant range promotes steep evolution
  - Rare source limit means merging bubbles make huge difference to ionizing background

Davies & Furlanetto (in prep)

Forest Evolution: Possibly!
The Temperature Field

Ionized Fraction

Temperature

430 Mpc

McQuinn et al. (2008)
Photoheating During Reionization

- Each ionization deposits several 10s of eV in IGM
- Expect ~10,000-30,000 K heating during reionization

Furlanetto & Oh (2008)
The Latest Observations

Becker et al. (2011)

Lidz et al. (2011)
Inside-Out Reionization and the Temperature Field

- **Dense regions** ionized first: end up coldest at end of reionization
- **Voids** ionized last: hottest

Furlanetto & Oh (2009)
The IGM Temperature During H I Reionization

- Strong evolution in “equation of state”
  - Lyman-series lines can probe different densities
  - May be observable!
  - J1148: strongly inverted temperature-density relation
  - Need ~10 excellent spectra to do carefully

Temperature Evolution: Possibly!

Oh & Furlanetto (2005)
The Dynamical Effects of Reionization

- Increased temperature also increases pressure
- Possibly dramatic effects during H I reionization
  - Minihalo evaporation
  - Suppression of accretion ("photosensitive halos")
  - IGM smoothing
- Can we detect this during helium reionization?
  - What happens to the H I forest?

Dynamical Evolution: Possibly!
Is He II Reionization an Analog for H I Reionization?

- Photon-counting: NO
  - Bubble evolution very different in rare, bright source limit
- LLS phase: YES (?)
- Fluctuating Lyman-α forest: NO
  - H I reionization much more uniform, fluctuations hidden by Gunn-Peterson saturation
- Average optical depth: MAYBE
- Temperature field: YES (?)
  - But probes themselves differ
- Dynamical effects of reionization: YES (?)
  - Currently a step beyond theory