the Hell Lyman-alpha forest

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most new science from MM & Worseck 2014
advertisement:
what your neighbors are working on

Phoebe Sanderbeck
Thermal history of $1 < z < 5$ IGM

John Ruan
Quasar feedback in $tSZ$ (w/ Scott)

Erik Anson (physics)
very early structures; first stars

Anson D’Aloisio
affect of small structures and gas relaxation on cosmological ionization fronts
my previous colloquium here was about IGM in early Universe; this time the focus is “late” times (\(z \sim 3\))

\[
\begin{align*}
\text{z} & \sim 20 \\
\text{z} & \sim 3 \\
\end{align*}
\]

VLT/UVES spectrum reduced by G. Worseck

Thursday, November 20, 14
my previous colloquium here was about IGM in early Universe; this time the focus is “late” times (z~3)

VLT/UVES spectrum reduced by G. Worseck

z~20

z~3

Thursday, November 20, 14
The z=3 IGM is an important checkpoint for models of cosmic evolution

We understand this! $z \approx 1100, \ t=400,000\text{yr}$

Intergalactic Medium
$z \approx 3, \ t=2\text{ Gyr}$

$\Omega_{\text{IGM}} \sim 1$

Galaxy/Star formation

$\Omega_{\text{Galaxy}} \sim 0.005$

$\Omega_{\text{crab}} = 10^{-25}$

Thursday, November 20, 14
The Universe’s ionization history

Recombination

He II $\rightarrow$ He I

$z \approx 3$

HI (and HeI) reionization

$H$ II $\rightarrow$ H I

$z = 11.1$

Hell reionization

Thursday, November 20, 14
After reionization of species X

fraction in state Y:

\[ x_Y = \frac{\alpha_Y n_e}{\Gamma_Y} x_Y I \quad Y \in \{\text{HI, HeI, HeII}\} \]

where the photoionization rate of species X is

\[ \Gamma_Y = \int_{\nu_Y}^{\infty} \frac{d\nu}{h\nu} \sigma_Y(\nu) J_\nu \]

\(\Gamma_{\text{HI}}\) and \(\Gamma_{\text{HeI}}\) dominated by stars or quasars. \(\Gamma_{\text{HeII}}\) dominated by quasars.
Quick intro into hydrogen Lyman-alpha forest
(e.g. how we know most things about diffuse IGM)
nice animation of Lyα forest

credit: Andrew Pontzen
nice animation of Lyα forest

credit: Andrew Pontzen
How we know most things about IGM after HI reionization: the Lyα Forest

from Bill Keel's website

\[ n_{HI} = \frac{\alpha_{HI} n_e^2}{\Gamma_{HI}} \]

\[ n_{HI}(z=3) \sim 10^{-11} \text{ cm}^{-3} \]

\[ \tau_{GP}(z) = 1.8 \times 10^5 h^{-1} \Omega_m^{1/2} \left( \frac{\Omega_b h^2}{0.02} \right) \left( \frac{1 + z}{7} \right)^{3/2} \left( \frac{n_{HI}}{n_H} \right) \]

Thursday, November 20, 14
Many studies have quantitatively compared simulations to observations of the Lyman-a forest.

Historic references: Miralda-Escude, Cen, Ostriker & Rauch '96; Hernquist, Katz, Weinberg, Miralda-Escude '96
end result: comparison of model to data
(model assumes uniform $\Gamma_{\text{HI}}$/simple temperature models)

McDonald et al 2006

Note: Your very own Vaishali is doing the same measurement in BOSS.
But, the “agreement” between simulations and the Lyman-alpha forest may be hiding things

- power spectrum changes very little if take absorbers and scramble them (Viel et al 2004)

- almost impossible to detect temperature (MM et al 2011) and ionizing background fluctuations (Croft ’04, McDonald et al ’05, MM et al 2011)
Is there another probe of the low density IGM?

Yes, the Lyman-alpha forest of Hell!!

304 A rather than 1216 A
This topic also has a history in this department

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RESOLVING THE HELIUM LYMAN-α FOREST: MAPPING INTERGALACTIC GAS
AND IONIZING RADIATION AT z=3¹

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MAPPING LOW-DENSITY INTERGALACTIC GAS: A THIRD HELIUM Lyα FOREST¹

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A HIGH YIELD OF NEW SIGHTLINES FOR THE STUDY OF INTERGALACTIC HELIUM: FAR-UV-BRIGHT QUASARS FROM THE SDSS, GALEX, AND HST⁸

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finding HeII forest quasars

Reimers et al ’92

Hell forest visible in 1% of sightlines; of order 20-30 sightlines are known that could be observed with HST (thank David Syphers and Scott).

For my analysis, I concentrate on brightest two.
the brightest HeII quasar

HST/COS observation of HE2347-4342

Shull et al 2010

\[ \tau_{\text{HeII}} = 3.4 \left( \frac{x_{\text{HeII}}}{0.01} \right) \left( \frac{1 + \delta}{0.1} \right) \left( \frac{1 + z}{4} \right)^{3/2} \]

for argument that GP trough => HeII region: MM 2009
the brightest HeII quasar

HST/COS observation of HE2347-4342

\[ \eta \equiv 4 \frac{\tau_{\text{HeII}}}{\tau_{\text{HI}}} \approx \frac{n_{\text{HeII}}}{n_{\text{HI}}} = 0.4 \frac{\Gamma_{\text{HI}}}{\Gamma_{\text{HeII}}} \]

Combination divides out density.
Our picture of the post-reionization ionizing background

source at $z=2.5$

e.g., Haardt & Madau '96
the post-reionization ionizing background is largely uniform

- $\lambda_{1\text{Ry}} = 800$ comoving Mpc at $z=2.5$
- $\lambda_{4\text{Ry}} = 100-200$ comoving Mpc at $z=2.5$

- Fraction of volume where background enhanced by factor of 2 over mean equals

$$f_{\text{proximity}} = \left(6\sqrt{\pi}\right)^{-1} n^{-1/2} \lambda_{\text{mfp}}^{-3/2}$$

or $\sim 1\%$ for quasars, $\sim 0.1\%$ for galaxies at $z=2.5$ at $1\text{Ry}$

and $\sim 20\%$ for quasars for HeII ionizing background (4 Ry)
HE2347-4342: Previous measurements of $\eta$ ratios

$$\eta \equiv 4 \frac{\tau_{\text{HeII}}}{\tau_{\text{HI}}} \approx 0.4 \frac{\Gamma_{\text{HI}}}{\Gamma_{\text{HeII}}}$$

Previous FUSE measurement, 140 hr

Recent COS HST measurement, 20 hr

see Shull et al '04, Zheng et al '04, Fechner & Reimers '07, Shull et al '10
``the η problem``

Possible solutions:

- interesting radiative transfer effects (Shull 2000 and many in field)
- galaxies (Miniati ’04; Khaire & Srianand ’13) or POPIII stars (Venkatesan et al ‘03)
- It’s just quasars and (very small) mean free paths (Bolton et al ’06; Furlanetto ’09)
- there is something wrong with the measurements
Concerns about previous $\eta$ measurements

- Most studies used estimator

- S/N of FUSE was $\sim 5$. One can only measure $\eta$ with standard estimator in pixels where $T_{\text{HeII}} > (S/N)^{-1}$. Assuming $\eta = 100$, this works out to $\tau_{\text{HI}} < 0.04 \ln([S/N]/5)$.

- for COS pixels are not resolved and one can show that standard estimator is always biased low

\[
4 \leq 4 \frac{- \log \left[ \int \exp(-\eta/4\tau) P(\tau) \, d\tau \right]}{- \log \left[ \int \exp(-\tau) P(\tau) \, d\tau \right]} \leq \eta
\]

MM & Worseck '14
This can be done better for COS by forward modeling

estimated HeII Transmission = \exp \left[ -\frac{\eta}{4} \tau_{\text{HI}} \right]

\textbf{Caveat 1:} This will be biased by mismatch in thermal broadening. Our mocks from cosmological simulations show that this bias is small.

\textbf{Caveat 2:} Continuum uncertainty in the HI forest is a big problem as a \( \tau_{\text{HI}} = 0.02 \) maps to \( \tau_{\text{HeII}} = 0.5 \) for \( \eta = 100 \)
We produced mocks that replicate the statistical properties of the data. Also mocks are fit HI data with same automated continuum fitting algorithm.

Noiseless mocks w/ input $\eta = 100$

We tuned continuum fitting algorithm to be unbiased on mocks.
Our $\eta$ measurement:

$$\eta \equiv \frac{n_{\text{HeII}}}{n_{\text{HI}}} = 4 \frac{\tau_{\text{HeII}}}{\tau_{\text{HI}}} \approx 4 \frac{\Gamma_{\text{HI}}}{\Gamma_{\text{HeII}}}$$

- green region = our measurement
- cyan = our’s with continuum errors
- grey dots = previous measurement
Our $\eta$ measurement:

$$\eta \equiv \frac{n_{\text{HeII}}}{n_{\text{HI}}} = 4 \frac{\tau_{\text{HeII}}}{\tau_{\text{HI}}} \approx 4 \frac{\Gamma_{\text{HI}}}{\Gamma_{\text{HeII}}}$$

green region=our measurement
cyan=our’s with continuum errors
grey dots=previous measurement
Second brightest sightline
What is expected level of $\eta$ fluctuations?

The statistics of both cases seem consistent w/ the observations (MM & Worseck ’14).
Other Implications:

- Quasar lifetimes: $\geq 10$ Myr

Proximate quasars identified in Worseck et al ‘07 and Shull and Syphers ‘13

These tentative detections add to the 1 other transverse proximity quasar that has been definitively detected that also suggest $t_{qso} > 10$ Myr (Jakobsen et al ‘03, Syphers & Shull 14).
Other implications 2:

• Quasars dominate $z \sim 2.5$ HI ionizing background

$$\alpha_{\text{eff}} = 1.92 + \log_4 \left[ \left( \frac{0.5}{\delta} \right) \left( \frac{8}{\lambda_{\text{HI}}/\lambda_{\text{HeII}}} \right) \left( \frac{\eta}{100} \right) \right]$$

where

$$\frac{\epsilon_{4\text{Ry}}}{\epsilon_{1\text{Ry}}} = 4^{-\alpha_{\text{eff}}}$$

(i.e. $\alpha_{\text{eff}}$ is unabsorbed effective 1-4Ry spectral index of EUV bkgd)
What’s next in diffuse z~3 IGM?

(1) Other observational probes

- Unfortunately, no large UV space telescopes planned that can be used to measure the $\text{HeI} \, 584\,\text{A}$ forest (McQuinn & Switzer 2010)

- the SKA should detect a forest of $^{3}\text{He}^+$ hyperfine absorption towards radio loud QSOs (McQuinn & Switzer 2009)
What’s next in diffuse z~3 IGM?

- **Amazing** quasar lifetime measurements from line-of-sight HeII proximity effect (in prep)

- I think a lot more information can be pulled out of the high-resolution HI Lyman-alpha forest data (and interesting evolution at z~6)

- testing models at higher intergalactic densities such as Lyman-limit systems (MM, Faucher-Giguere, & Oh 2011 and Altay et al 2011)
Conclusions

• Radiative backgrounds are doing as expected: *No evidence for large ionizing background fluctuations*

• Hardness of ionizing background *consistent* with *quasars* sourcing HI and HeII ionizing backgrounds at \( z=2.5 \)

• Interesting *quasar lifetime inferences* of \( \geq 10 \text{ Myr} \) (with plans to improve this)