How Supermassive Black Holes Ignite the Intergalactic Medium: Tales from the Low Redshift Lyman-\(\alpha\) Forest
Outline

• What is the Ly-\(\alpha\) Forest?

• The incredible observational and theoretical successes of the Ly-\(\alpha\) Forest from 1.6<\(z\)<6: Providing insights into cosmology, the ultraviolet background, and the intergalactic medium

• The incredible observational and theoretical mysteries of the Ly-\(\alpha\) Forest at \(z<1\): cosmological simulations in crisis? New physics?

• How the growth of supermassive black holes heat up the IGM and alleviate (most) of the tension
Ly-\(\alpha\) Forest: An Invaluable Tool for Studies of the IGM and Cosmology

Gunn and Peterson (1965);
Bahcall and Salpeter (1965)
• What is the Ly-α Forest?

Insights from these observations:

• The IGM is Highly Ionized: Gas between us and these quasars has low HI optical depths which is due to ionization by quasars and star forming galaxies.

• The End of the epoch of reionization: At highest redshifts observed (z~6), there are no more “trees in the forest” as optical depth increases due to natural fraction increasing (i.e. Gunn-Peterson Trough).

At low redshift, forest is less “thick” —> lower cosmic density (lower optical depth)

\[ F = 1 - e^{-\tau} \]
What is the Ly-α Forest?

Ionization Equilibrium of hydrogen with the background UV Field

\[ n_{\text{HI}} \Gamma = n_{\text{HII}} n_e \alpha(T) \]

\[ \tau_{\text{IGM}}(z_a) \approx 2[1 + \delta_b(z_a)]^2 \frac{\alpha_{\text{rec}}(T)}{\Gamma} \left( \frac{1 + z_a}{4} \right)^{4.5} \]

- \( z_a \): Redshift of absorbing gas
- \( \delta_b(z_a) \): baryonic overdensity of absorbing gas
- \( T \): temperature of absorbing gas
- \( \Gamma \): photoionization rate at absorbing gas = strength of ionizing BG.

Insights from these observations:

- **The IGM is Highly Ionized**: Gas between us and these quasars has low HI optical depths.
- **The End of the epoch of reionization**: At highest redshifts observed (z~6), there are no more “trees in the forest” as optical depth increases due to natural fraction increasing (i.e. Gunn-Peterson Trough).
- **IGM Physics and Cosmology** science are possible via analysis of HI photoionization equilibrium.

\[
F = 1 - e^{-\tau}
\]

Represents an important result as it links the observed opacity in Lyα forest to:
- density of the matter field
- temperature of the gas at that point
- ionizing radiation background.

Moreover, it enables us to understand & interpret basic observations of the Lyman alpha forest.
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• Future outlook for low redshift 21-cm mapping and machine learning studies
• Ly-α Forest: provides ionizing background (UVB)

- Post-reionization: spatial uniformity of the UVB
- Census of ionizing photons and hardness of radiation from QSOs and galaxies (escape fractions)
- Photoionization equilibrium provides coupling of the HI column density to UVB
- Measuring column density distribution —> gives Gamma

\[ J_\nu \propto \nu^{-\alpha+3[1-\beta]} \] for \( \partial^2 N / \partial x \partial N_{\text{HI}} \propto N_{\text{HI}}^{-\beta} \) and \( \epsilon \propto \nu^{-\alpha} \)

\[ \Gamma \equiv 4\pi \int_{\nu_{\text{HI}}}^{\infty} \frac{d\nu}{b\nu} \sigma_{\text{HI}}(\nu) J_\nu \]

- \( J_\nu \): angularly averaged specific intensity of ionizing background
- \( \Gamma \): photoionization rate of HI
z>2 Ly-α Forest: Observations and Numerical Simulations Agree!!

The beautiful match of LCDM cosmological hydro simulations with Ly-α Forest observations puts the cosmological paradigm on very firm footing!

Time evolution of a 10Mpc (comoving) over-dense region within a cosmological simulation.

Movie: Illustris Team
The column density distribution function (CDD) measures the fine-grained clumping and structure of the forest.

The CDD depends on the photoionization rate, density, and the temperature of the IGM.

All these components are well understood at z>7 in LCDM and included in cosmo-sims:

Photoionization from quasars (z<4) and star forming galaxies (z>4), temperature set by heating (photoheating) balancing cooling (adiabatic expansion), and density set by the dark matter distribution.
z>2 Ly-γ Forest: A Tool for Precision Cosmology

The beautiful match of LCDM cosmological hydro simulations with Ly-γ Forest observations puts the cosmological paradigm on very firm footing!

Acoustic Peak in Lyα Forest.

Recent Lyman alpha forest measurements (BOSS) have uncovered the acoustic peak in the matter power spectrum (i.e. the acoustic peak imprints itself also in Lyman alpha forest)

Flux power spectrum to matter power spectrum

Croft et al. 1998
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Low Redshift Lyman-\(\alpha\) forest

Why care? “New physics is at high redshift” - Sultan

Most baryons are in the IGM:
Even after nearly 14 Gyr of evolution, only a small fraction of baryonic matter has collapsed into luminous objects (galaxies, groups, clusters) while \(\sim 80\%\) are in the IGM!

Low z Forest is Hard:
1) From 1>z>2 we have no good tracers of the Forest

2) z<1 requires space based UV instrumentation
   COS
   FUSE
   GALAX

   Landmark study Danforth et al. 2016: largest sample of low-z absorbers to date and is more sensitive than previous studies.

3) Cosmological simulations: baryonic feedback effects become more important and non-standard heating sources can be present (e.g. shocks)
Low Redshift Lyman-\(\alpha\) forest: observations vs simulations

Mismatch between observed data and simulations.

- 5 times stronger UVB required at \(z=0.1\)!

Kollmeier et al. 2014 first reported a discrepancy in the column density distribution at \(z=0.1\) with simulations which include the Haardt & Madau (2012) UV-background model.

To achieve the correct UVB the ionizing photons must be increased by a factor of 5 over HM12!
IGM with x5 different ionizing photons: dramatically different IGM

Kollmeier et al. 2014
Initial ideas as to what could be going on..

- Not enough photons are accounted for in the simulations? UV Background is actually higher (factor of 5).
- Galaxy escape fractions/quasar luminosity boosted?
- Extra heating terms?
- Exotic sources of photons like DM decay?
- Some combination of the above?
Can Updated UVB Models Save the Day?

UVB models since Kollmeier et al. 2014 provide at most factor of 2.5x more ionizing photons than HM12.
Column Density Distribution performs much better (at low column density) than expected for the FG09 UVB!

Extra heating?
Why does the CDD in Illustris fit the COS data better?

Our 2017 study addressed the effects of:

• UV Background (UVB) ?
• Resolution?
• Hydrodynamics?
• Stellar Winds?
• AGN Feedback?

The Effect of AGN Heating on the Low-redshift Lyα Forest

Alex Gurvich¹, Blakesley Burkhart², and Simeon Bird³
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The Astrophysical Journal, Volume 835, Number 2
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DOI 10.3847/1538-4357/835/2/175
As expected, FG09 UVB isn’t enough to fully solve the discrepancy.

More ionizing UVB + additional heating needed.

Gurvich, Burkhart & Bird 2017
Stellar Feedback

GADGET sims (Kollmeier et al. 2014)

Illustris: FG09

Stellar Feedback Only

NO Feedback

Hubble data D16

\( \frac{d^2N}{d \log N dz} \) vs \( \log (N) \)

Gurvich, Burkhart & Bird 2017
AGN Feedback and the Column Density Distribution in Illustris

Subsequent papers confirmed the importance of AGN feedback for the low redshift Lyman:

Viel et al. 2017
Tonnesen et al. 2017
Nasir et al. 2017
Christiansen et al. 2020

\[ \tau \propto n_{\text{HI}} \propto \rho^2 T^{-0.7} \Gamma^{-1} \]

Increase in UVB will decrease NHI
Increase in temperature will decrease NHI
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Low Redshift Lyman-α forest: observations vs simulations

The AGN feedback model can have a major effect.

Burkhart et al. 2022
Why is this not a problem at $z>2$?

Growth of blackholes and AGN heating not significant (volume filling) until lower redshift.
$z = 5.04$

Simba cosmological simulation
Christiansen et al. (2020)
Other Statistics: $b$ distribution

- TNG and Illustris are too narrow compared to COS!
- Could be unresolved turbulence?
- Likely not Jeans broadening - widths in the diffuse IGM at $z \sim 0.1$ have a minimal contribution from Jeans smoothing since $b_{\text{Jeans}}^2 \propto \Delta^{-1}$ and $\Delta=10$ at $z=0.1$

\[
b_{\text{turb}}^2 = b_{\text{obs}}^2 - b_{\text{noturb}}^2
\]

\[
b_{\text{obs}}/b_{\text{therm}} \approx 1.24
\]

\[
b_{\text{turb}} \approx 0.73 b_{\text{therm}}
\]
Conclusions

- **High-z Ly-α Forest:** a happy place for cosmologists where baryons are well-behaved (i.e., follow dark matter and equilibrium).

- **Low-z Ly-α Forest:** Ly-α Forest baryons are no longer following the classic paradigm. AGN Feedback can have a significant impact on the low-z Ly-α forest via heating and matter redistribution (a “Forest Fire!”).

- The particulars of the AGN feedback model have a dramatic effect on the Ly-α forest (i.e., TNG vs Illustris vs Simba etc.).

- Bad news: UVB measurements from Ly-α forest are dangerous at low z!

- Good news: We can calibrate feedback models on z=0.1 forest!

- The AGN “Forest Fire” begins around z=1 (sooner for damped Lyman-α systems).

- Machine learning can likely help disentangle the parameters (let’s discuss more!)
Voigt vs. Direct Calculation

\[ \frac{d^2 N}{d \log N \, dz} \]

- Direct
- Voigt

\[
\log (N)
\]

- Direct
- Voigt
## New AGN Model for TNG

**Illustris**

<table>
<thead>
<tr>
<th>Black Hole Formation</th>
<th>( M_{BH} = 10^5 M_\odot ) seeded inside all haloes with</th>
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| Black Hole Growth    | \( \dot{M}_{BH} \)

- All accretion rates Eddington limited:
  \( \dot{M}_{\text{eff}} = \min\left( \dot{M}_{\text{Bondi}} \right) \)
  \( \dot{M}_{\text{Bondi}} = \frac{100}{\text{min}} \dot{M}_{\text{Bondi}} \)
  \( \dot{M}_{\text{Bondi}} \max \left( 1, \frac{M_{BH}}{M_{\text{pivot}}} \right) \)

**Quasar Feedback**

- \( \dot{M}_{\text{eff}} > 0.01 \dot{M}_{\text{Edd}} \)
- \( \dot{M}_{\text{eff}} > 0.05 \dot{M}_{\text{Edd}} \)

\( \dot{E} = \epsilon_f \epsilon_r \dot{M}_{\text{eff}} c^2 \) distributed isotropically

*Courtesy of C. Popa*
Radio Feedback (slow growth)

\[ \dot{E} = \epsilon_f \epsilon_r M_{\text{eff}} c^2 \]

- \( \epsilon_f = 0.35 \)
- \( \epsilon_f = 0.07 \)
- \( \epsilon_f = 0.1 \)

\[ \dot{M}_{\text{eff}} < 0.01 \dot{M}_{\text{Edd}} \]

Thermal feedback inflates 1 hot bubble

\[ R = R_0 \left( \frac{E}{E_0} \right)^{1/5} \left( \frac{\rho_{\text{gas}}}{\rho_0} \right) \]

\[ E = \epsilon_f \epsilon_r c^2 \delta M_{\text{BH}} \]

\[ \dot{M}_{\text{eff}} < 0.05 \dot{M}_{\text{Edd}} \]

Kinetic feedback momentum distributed isotropically to neighboring gas cells

100 kpc

Courtesy of C. Popa