AST4320 - Cosmology and extragalactic astronomy

Lecture 15

The Lyman Alpha Forest II
Lecture 15

Outline

- What is the Lyman alpha forest (continued)?
- Is the intergalactic medium really ionized?
- Constraints on matter distribution.
- Lyman limit systems and damped lyman alpha absorbers
The Lyman Alpha Forest

**Lyman alpha forest:** collection of Lyα absorption line features observed in spectra of bright quasars (see below).

Quasars - or active galactic nucleus (AGN) - are among the brightest sources in our Universe. Has spectrum of photons that extends to high energies.
The Lyman Alpha Forest

The thicker the forest, the lower the **mean transmission** and the higher the **effective optical depth**. Some observations:

\[
T \equiv \frac{\int d\nu J(\nu) T(\nu)}{\int d\nu J(\nu)}
\]

\[
T_{\text{eff}} = -\ln\langle T \rangle
\]

**Effective optical depth** increases with redshift, reaches unity at \( z \sim 4 \).
Physical Constraints on the IGM

Under the assumptions that
(1) baryons are distributed uniformly throughout the Universe, and
(2) that all hydrogen is neutral, we derived that

$$\tau_{\text{IGM}} = 1.7 \times 10^5 \left( \frac{1 + z}{4} \right)^{1.5}$$

In other words, if the IGM were neutral the Lyman alpha forest would be extremely opaque at mean density.

The fact that there are 5 orders of magnitude between the predicted and inferred IGM opacity, implies the IGM was highly ionized hydrogen, with only 1 part in $1e5$ neutral.
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The fact that there are 5 orders of magnitude between the predicted and inferred IGM opacity, implies the IGM was highly ionized hydrogen, with only 1 part in 1e5 neutral.

Some valid concerns:

- Could the intergalactic medium be simply empty?
- If there is so much more ionized gas in the IGM, can we see that?
- If IGM is highly ionized at \( z < 6 \), can radiation not couple again to the gas as was the case before the Universe recombined?
The Visibility of the Ionized IGM?

• Could the intergalactic medium not be empty?
• If there is so much more ionized gas in the IGM, can we see that?

Yes
The Visibility of the Ionized IGM?

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Yes. Free electrons in the ionized IGM can Thomson scatter photons. The total opacity in the ionized IGM to Thomson scattering is [derived on board]

\[ \tau(z) = \sigma_T c \int_0^z \frac{n_e(z) \, dz}{H(z)(1 + z)} \]
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\[ \tau(z) = \sigma_T c \int_0^z \frac{n_e(z) \, dz}{H(z)(1 + z)} \]

If the IGM were fully ionized out to \( z = 10 \), then the total optical depth is about 0.07. This optical depth can be interpreted as the `scattering probability'.
Free electrons in the ionized IGM can Thomson scatter photons.

\[ \tau(z) = \sigma_T c \int_0^z \frac{n_e(z) dz}{H(z)(1+z)} \]

T-fluctuations in CMB constrain \( \tau \) because scattering washes out structure in CMB: suppresses powerspectrum.

Scattering polarizes CMB, and constraints can be inferred from polarization EE power spectrum.

Planck measured \( \tau(z_{\text{rec}}) \approx 0.09 \pm 0.01 \). There is a substantial amount of free electrons between us and the CMB.
The Visibility of the Ionized IGM?

SO...
The Visibility of the Ionized IGM?

1. Primordial plasma recombined. Otherwise, we would not see primordial T-fluctuations.
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2. CMB also indicates that there exists a large amount of electrons in between us and CMB.
The Visibility of the Ionized IGM?

1. Primordial plasma recombined. Otherwise, we would not see primordial T-fluctuations.

2. CMB also indicates that there exists a large amount of electrons in between us and CMB.

3. Lyman alpha forest opacity at z<6 is low. Suggests IGM was highly ionized.
The Visibility of the Ionized IGM?

The simplest picture we have is that the IGM if fully ionized between $z=0$ and $z=6-10$ (and possibly partially ionized out to some higher redshift $z$). It is neutral between this redshift and the redshift of recombination $z_{\text{rec}} \sim 1100$. 

$z \sim 10$; IGM is ionized.

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Matter-Radiation Coupling in Ionized IGM?

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Matter-Radiation Coupling in Ionized IGM?

What is radiation `background' today anyway?
`Background' means present everywhere.

spectrum of radiation
Matter-Radiation Coupling in Ionized IGM?

What is radiation `background' today anyway? `Background' means present everywhere.

In spite of the ubiquitous presence of galaxies, accreting black holes, the radiation content of the Universe is dominated by the Cosmic Microwave Background.
Matter-Radiation Coupling in Ionized IGM?

The coupling between radiation and matter prior to recombination was via Thomson (electron) scattering.

We computed that the optical depth through the ionized IGM is low, $\tau = 0.09$. This implies that the majority of CMB photons ($\sim 91\%$) do not scatter at all in IGM. Photons `stream’ right through IGM.

No `tight’ coupling between CMB and baryons (.......though it would still be a good calculation to check the rate at which a free electron scatters CMB photons).
End Intermezzo
We derived that the opacity in the photoionized IGM was given by

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

- \( z_a \): Redshift of absorbing gas
- \( \delta_b(z_a) \): Baryonic overdensity at \( z_a \)
- \( T \): Temperature of absorbing gas
- \( \Gamma \): Photoionization rate at absorbing gas = strength of ionizing BG.
- \( \alpha_{\text{rec}}(T) \): Recombination coefficient; Contains all detailed physics.
  Is a function of gas temperature \( T \).
The Opacity of the Photoionized IGM

We derived that the opacity in the photoionized IGM was given by

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

- $z_a$: Redshift of absorbing gas
- $\delta_b(z_a) = \delta$: matter overdensity at $z_a$
- $T$: temperature of absorbing gas
- $\Gamma$: photoionization rate at absorbing gas = strength of ionizing BG.
- $\alpha_{rec}(T)$: recombination coefficient; Contains all detailed physics. Is a function of gas temperature $T$. 
The equation

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

Represents an important result as it links the observed opacity in Lya 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.
Intepreting the Lya Forest

This equation enables us to understand & interpret basic observations of the Lyman alpha forest. The redshift evolution of the effective optical depth is reproduced well.

\[ \tau_{\text{eff}} = A(1+z)^{4.5} \]

Fan et al. 2006
Intepreting the Lya Forest

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

\[ \alpha_{\text{rec}}(T) \sim 10^{-13} \, \text{cm}^3 \, \text{s}^{-1} \quad \text{for} \quad T \sim 10^4 K \]

\[ \tau_{\text{eff}} \sim 0.3 \quad \text{at} \quad z = 3 \]

\[ \Gamma \sim 10^{-12} \, \text{s}^{-1} \]

The fact that our model reproduces the observed z-evolution so well suggests that this photoionization rate cannot change much over this z-interval.
Interpreting the Lya Forest

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tau$_{\text{eff}}$ represents an average quantity, so we can use average density, i.e. delta=0

\[ \Gamma \sim 10^{-12} \text{ s}^{-1} \]

Photoionization rate appears not to evolve much between $z=2-4$ (which amounts for a cosmological time span of $\sim 2$ Gyr!)
Interpreting the Lya Forest

Photoionization rate appears not to evolve much between $z=2-4$, which provides some remarkable insights into galaxies & accreting black holes.

To derive on board.
Olbers Paradox Visually
Interpreting the Lya Forest

Photoionization rate appears not to evolve much between $z=2-4$, which provides some remarkable insights into galaxies & accreting black holes.

On the board, we derived that the photoionization rate relates to

$$\Gamma = \epsilon(\nu_L) \lambda_{\text{mfp}}^{\text{ion}} G(\alpha)$$

$G(\alpha)$ Function that depends on spectrum and known constant. **Known.**

$\lambda_{\text{mfp}}^{\text{ion}}$ Mean free path of ionizing photons, is limited by Lyman-Limit systems (discussed in a few slides). **Can be inferred** from data independently.

$\epsilon(\nu_L)$ Depends on sources of ionizing radiation: star forming galaxies accreting black holes, but contains contribution from galaxies that are too faint to be observed!

Recall, luminosity density is:

$$L = \int_0^\infty dL \ L \phi(L) = \phi_* L_* \Gamma(\alpha + 2) \quad \phi(L) \equiv \frac{dn}{dL} = \phi_* \left(\frac{L}{L_*}\right)^\alpha \exp\left(-\frac{L}{L_*}\right)$$
Interpreting the Lya Forest

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$\varepsilon(\nu_L)$ Depends on sources of ionizing radiation: star forming galaxies accreting black holes, but contains contribution from galaxies that are too faint to be observed!

**Equally important:** the fact that ionizing photons have a finite mean free path - which is typically much smaller than the horizon size- directly implies it is very difficult to detect ionizing radiation from galaxies directly!
Interpreting the Lya Forest

\[ \Gamma = \epsilon(\nu_L) \lambda_{\text{mfp}}^{\text{ion}} G(\alpha) \]

Example: comparison of observed Gamma with that expected from quasars.

Quasars appear to be able to account for all ionizing flux at z<3, but not beyond.

Motivation for claim that `star forming galaxies are responsible for reionization’
Interpreting the Lya Forest

The Lyman alpha forest appears to probe only small overdensities.

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

\[ \alpha_{\text{rec}}(T) \sim 10^{-13} \text{ cm}^3 \text{ s}^{-1} \text{ for } T \sim 10^4 K \]

\[ \Gamma \sim 10^{-12} \text{ s}^{-1} \]

\[ \tau_{\text{IGM}}(z_a) \approx 0.2[1 + \delta(z_a)]^2 \left( \frac{1 + z_a}{4} \right)^{4.5} \]

Fluctuations in flux correspond in fluctuations in tau, which in turn correspond to density fluctuations along line-of-sight.
The Lyman alpha forest appears to probe only small overdensities.

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$$

Fluctuations in flux correspond in fluctuations in tau, which in turn correspond to **density fluctuations** along line-of-sight.
Interpreting the Lya Forest

The Lyman alpha forest appears to probe small overdensities.

Just to stress: we are using quasar absorption line spectra to infer small density fluctuations in the dark matter in the Universe. Boom.

In fact, for many purpose it is possible to model Lyman alpha forest using dark matter simulations only!

This further illustrates how well the Lyman alpha forest can map out the (dark) matter distribution throughout the Universe.
Lya Forest - Matter Connection

We should be able to recover **key statistical properties** of the matter field, such as the matter power spectrum, and its correlation function.

BOSS Lyman alpha forest survey aims to `map’ out matter distribution using the Lyman alpha forest measured in a large number of background quasars (active galactic nuclei).
If observed opacity in Lya forest is linked to \textit{density} of the matter field, then we can should be able to recover \textbf{key statistical properties} of the matter field, such as the matter power spectrum, and its correlation function.

\textbf{Note}: matter distribution is sample along thin `skewers’. Constraining quantities like the 3D matter power spectrum is not trivial.
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Acoustic Peak in Lya Forest?

The acoustic peak represents an important feature in the two-point function of matter. If the Lyman alpha forest indeed provides such a great probe of the matter, the do we see this acoustic peak in the Lyman alpha forest?
Acoustic Peak in Lya Forest.

Yes, recent Lyman alpha forest measurements (BOSS) have uncovered the acoustic peak in the Lyman alpha forest.

Slozar et al. 2013
Connecting Lya Forest to Matter Power Spectrum

Recall that Lya absorption cross-section of photoionization gas is \( \sim \) few tens of km/s wide. Absorption features cannot be narrower than this `thermal width' \( v_{th} \).

**Thermal width** \( v_{th} \) imposes minimum distance in redshift space that can be probed, or -in other words - a maximum wavenumber.

Show in the **assignment** that a minimum velocity resolution of \( v_{th} \sim 20 \text{ km/s} \) translates to \( k_{\text{max}} \sim 10 \text{ cMpc}^{-1} \).
Constraints on (Warm) Dark Matter

Observational constraints
mass power spectrum

Lyman alpha forest indicates that $m_{\text{DM}} > \text{keV}$
Lya Forest In Galaxy Spectra!

Bright quasars are rare objects. Low space density limits sampling of Lya-forest.

Just now, first measurements of Lya forest in galaxy spectra.

Pro: Galaxies are more abundant

Con: Galaxies are fainter. Good signal-to-noise only in lower spectral resolution spectra.

Lya forest in galaxies allow for precise measurements of matter distribution on somewhat larger scales.
Lya Forest In Galaxy Spectra!

This month!

Portrait of the universe as a young man
High Column Density Absorbers: Towards Galaxies

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

Also recall that $\delta \sim 178$ the moment a dark matter halo virialized.

Virialized (a.k.a. collapsed) structures must correspond to large overdensities in the Lya-forest.

The most opaque absorption line systems in the Lyman-alpha forest are

- Lyman Limit Systems (LLSs); defined as having $N_{\text{HI}} > 10^{17} \text{ cm}^{-2}$.
  This corresponds to an optical depth $\tau_{\text{IGM}} \gtrsim 10^4$
  
  This definition has a physical origin: at $N_{\text{HI}} > 10^{17} \text{ cm}^{-2}$ opacity to ionizing photons > 1.

- Damped Lyman Alpha Absorbers (DLAs); defined as having $N_{\text{HI}} > 10^{20} \text{ cm}^{-2}$.
  This corresponds to an optical depth $\tau_{\text{IGM}} \gtrsim 10^7$

DLAs are associated with galaxies (next slide)
Damped Lyman Alpha Absorbers

Damped Lyman Alpha Absorbers (DLAs) are defined as having $N_{\text{HI}} > 10^{20} \text{ cm}^{-2}$

Recall from lecture on cusp-core problem in which we discussed HI rotation curves.

Stars are shown in white. HI (neutral atomic hydrogen gas) in purple.

Existing radio telescope can only detect 21-cm in emission for HI column densities $\sim N_{\text{HI}} > 10^{20} \text{ cm}^{-2}$

This gas is basically associated with galaxies.
Damped Lyman Alpha Absorbers

An example:

Note how far the absorption extends away from line center!

Recall shape of the absorption cross-section (next slide): absorption cross-section drops by orders of magnitude away from line center/resonance, but does not vanish.

We can see the effect of this non-vanishing cross-section in quasar spectra.
The Lyα Absorption Cross-Section

Absorption cross-section: Because cross-section is so sharply peaked in frequency, I show it here as a function of velocity off-set from line center.

Width is few tens of km/s for $T=10^4$ K

$\Delta \nu / \nu \sim 10^{-4}$

'damping wing' of absorption cross-section
Lyman Limit Systems

We discussed how most absorption lines in the Lya forest correspond to mildly overdense regions with \( \tau \sim 1 \) and \( \Delta \sim 1 \).

We also discussed how the most opaque absorption line systems, with \( \tau_{\text{IGM}} \gtrsim 10^7 \), are [likely] associated with galaxies.

It would seem logical that gas in absorption line systems of `intermediate’ opacity are associated with `intermediate’ stages of galaxy formation, e.g. gas that is assembling inside galaxies, or alternatively, gas that has been pushed back out.
Lyman Limit Systems

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Conclusions 1/2

Lyman alpha forest is a series of Lyman alpha absorption lines in the spectrum of distant quasars/active galactic nuclei (bright sources powered by accretion onto a supermassive black hole).

The observed opacity of the Lya forest - combined with inferred column density of electrons out to very high redshift, as inferred from CMB - implies that the intergalactic medium (IGM) is **highly ionized** (most likely photoionized).

IGM must have been **reionized** at some point in our distant past.

The observed opacity in Lya forest constrains
- **density** of the matter field
- **temperature** of the gas at that point
- **ionizing radiation** background.

Statistical properties of Lyman alpha forest provide constraints on matter powerspectrum/two-point function: the **acoustic peak has been detected**.
Conclusions 2/2

**Constraints on mass of dark matter particle** limited to \( m > 1 \) keV by thermal broadening of absorption lines in Lyα forest.

**Photoionization rate in IGM** appears constant between \( z=2-4 \), and cannot be accounted for by bright quasars at \( z>3 \); dominated by star forming galaxies?

Most absorption lines correspond to mildly overdense regions with \( \tau \sim 1 \) and \( \delta \sim 1 \). 

The most opaque absorption line systems (Damped Lyman Alpha systems), which have \( \tau_{\text{IGM}} \gtrsim 10^7 \) are [likely] associated with galaxies.

Nature of absorption line systems of intermediate opacity (Lyman Limit Systems) is not clear, but would seem logical to connect to ‘intermediate’ stages of galaxy formation.

**Next lecture** we talk more about how galaxies get their gas and form stars.