Lyman-Alpha Forest as a new powerful astronomical tool

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1 The Lyman-Alpha Forest

If we assume the universe to be filled up with Hydrogen floating around, light from far-away objects should be absorbed and remitted by the Hydrogen atoms. The most possible such transition happens to be the transition from n=2 to n=1 state, releasing light of wavelength $121.5nm$.

As the universe expands, Hydrogen atoms of different distance from Earth will have different velocities, and thus different Redshift, as the cosmological Redshift is given by:

$$z = \frac{H_0 D}{c} = \frac{\Delta\lambda}{\lambda}$$

Gunn & Peterson [6] predicted that, if we have a universe filled homogeneously with Hydrogen (that is the entire universe is a huge Hydrogen blob with uniform density), Hydrogen will eat up everything between the original Lyman-Alpha line and the most red shifted Lyman-Alpha line.

Lets start our journey from the far far away quasar with its emitted continuous light. The light will pass through some Hydrogen nearby and have some light absorbed at the wavelength $121.5nm$. Then as the light go further, this absorbed gap got shifted to the red. When the light meet the next Hydrogen, the Hydrogen will take out the $121.5nm$ line again. As the $121.5nm$ gap created by the previous Hydrogen has already shifted away, a new gap is created at this wavelength.

By Gunn & Peterson's [1] prediction, the absorption is of order[1]:

$$I = I_0(1 - e^{-p})$$

where as:

$$p(\nu) \propto \frac{n_s}{(1 + z(\nu))(1 + 2q_0 z(\nu))^{1/2}}$$

for which n_s is the neutral Hydrogen density and q_0 is the deceleration parameter.

That is to say, if Hydrogen is uniformly distributed in the space, we should see a great trough in the spectrum, between the wavelength of $Ly\alpha$ to $Ly\alpha(1 + z)$. However, this was not seen.

What was seen is many lines between $Ly\alpha$ and $Ly\alpha(1+z)$, people see a bunch of absorption, looking like a forest.

This result was proposed by Bahcall & Salpeter (1965), that a discrete number of absorption will be seen in the spectrum. What this spectrum tell us is fairly straightforward: The universe is not entirely uniform in density, and have a lot of blobs. When the light from the quasar passed a blob, the blob will create a $Ly\alpha$ absorption. The light will then propagate with a absorption line in the spectrum, and as distance pass, red shifted when it reaches the next blob. Here the light gets absorbed and Red shifted again, leaving another mark in the spectrum. Moreover, a more general and easy to read model of the Lyman-Alpha Forest spectrum is as follows. The location of the different Lyman lines are marked (1).

As you can see, although we call this the Lyman-alpha forest, all other absorption lines will also create their own forest. The good news is, you will have the information of the lines at any distance on the line of sight, as they are all embedded in the single spectrum! However, the bad news is that these forests will also merge into each other, and its challenging to tell them apart sometimes.

[1]See Gunn & Peterson 1st and 2nd pages [6]

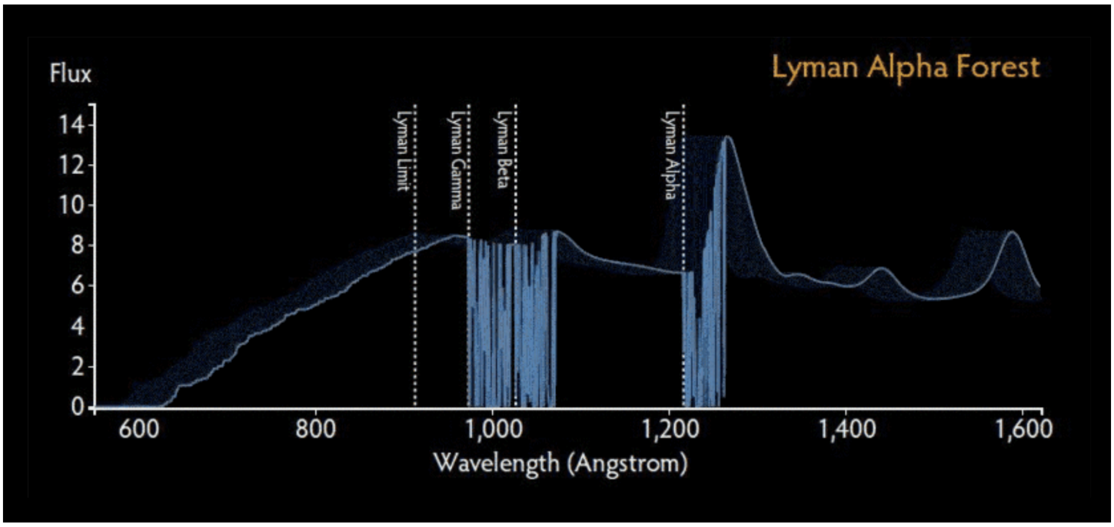

Figure 1: Overview of Lyman Alpha Forest

2 Inter-Galactic Medium

Since one absorption line is created every time the light passes through a blob of Hydrogen in space, it would be a good idea to use these lines to probe their distributions [9].

Here, we will look at every "tree" in the forest, referring to each gap here, and discuss their wavelength, depth, width, and related trees (trees created at the same red shift, or to say trees created by the same Hydrogen blobs).

2.1 Wavelength (distance & size)

The first thing is of course the specific red shift of each tree, indicating how far are they from us. This part is simple, just find the "tree" you are interested in this forest, measure it's red shift, through the Hubble constant at it and duh, you have the distance:

$$z = \frac{D}{c} H_0$$

From the red shifts of the trees, we can obtain a general idea of the distance between the trees and us, thus the distance between different trees, giving us an idea of how matter is distributed in the universe. This will not only help giving us a general idea of the distribution of the Inter Galactic Medium, but also help us understand the nature of dark matter, as will be discussed later.

2.2 Depth (density & mass)

Then we look at the depth. Using the Gunn & Petterson result, we can relate the column density and the depth of Hydrogen.

The original intensity of the Quasar can be modeled by looking at the overall trend of the spectrum. Then we look how many of the intensity got eaten up by the tree we are interested in. Finally we say something about how many Hydrogen is required to eat up so many. Which is, relating back to the size factor from the previous analysis, giving out a total mass of the Hydrogen blobs.

2.3 Width (temperature & energy)

As spectrum, they definitely have width. With width, we can tell the velocity dispersion, which is temperature. Just like we did in class:

$$z = \frac{\Delta\lambda}{\lambda} = \frac{v}{c} = \sqrt{\frac{3k_B T}{mc^4}}$$

2.4 Neutral Fraction (energy state analysis)

By looking into the intensity distribution of Lyman lines, we can then place a boundary condition onto the wave function of the Hydrogen atoms in the medium, and then calculate the possibility of a given Hydrogen is in it's ground state. The math is kind of grouse, but the basic idea is that, given the Lyman-alpha and Lyman-beta intensity, you obtain a boundary condition for the wave function you are looking at. Then you just solve for the probability of that wave function collapsing into the ground state, and that is the neutral fraction .

The following figure shows the Neutral Fraction and Temperature of the Hydrogen blobs far away from us. The measurements done by Lyman-Alpha Forest is marked green:

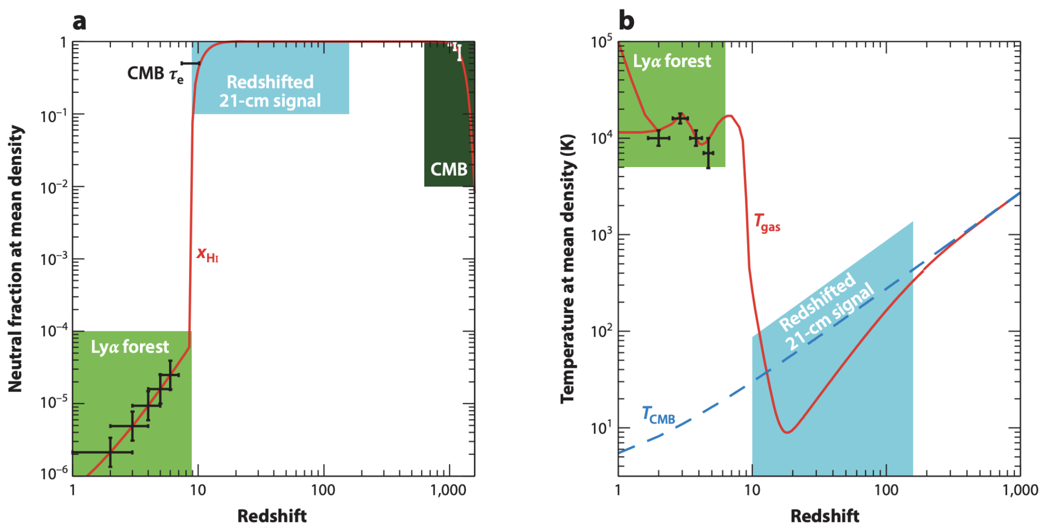

Figure 2: Diagram showing the ionization and thermal history of intergalactic gas. The red curves show a model of intergalactic gas. Error bars symbolize existing constraints, and the highlighted regions illustrate the potential purview of the named cosmological probe. In the temperature panel, the model curve bifurcates at low redshifts to indicate the intergalactic medium (IGM) temperature becoming multiphase [10]

3 Structure Formation, CDM, HDM

From Lyman-Alpha Forest we know that blobs of Hydrogen exist in between us and the Quasars. It is then interesting to discuss what kind of distribution they have, and what we can infer from that. Following is a simulation of the distribution of these blobs

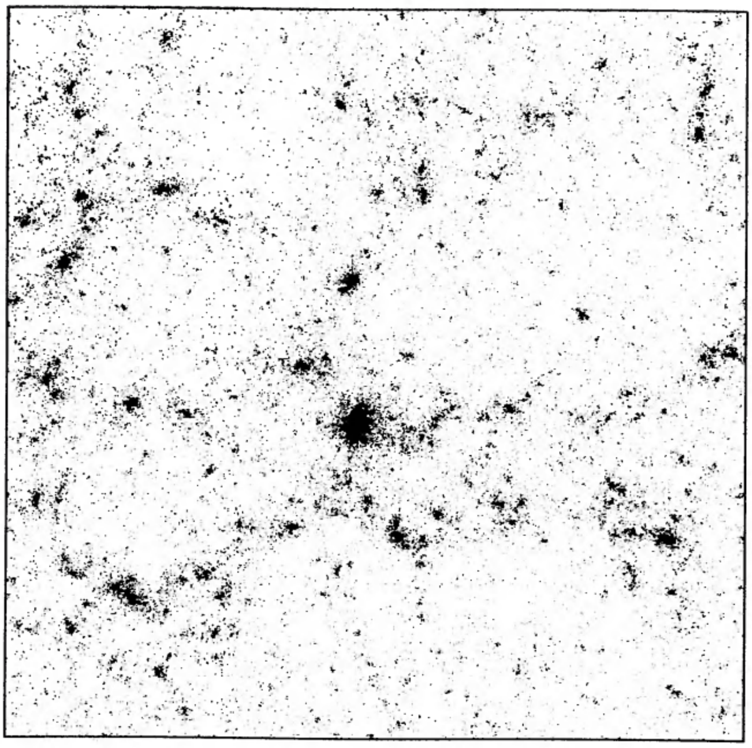

Figure 3: Large Structure Simulation assuming Cold Dark Matter [4]

The secret of matter in our universe is that, they want to gather into potential wells, and stay there forever, when they do not have much energy. The fact that there is a forest instead of a trough indicated that, these matter does fly around the universe, but tend to quietly gather in potential wells.

An analysis can be done regarding the free fall time interval [11]. If we look into the Jeans scale, it means everything smaller than this scale will be collapsing inward and form a structure. However, the free streaming scale say that a particle will eventually talk to another particle after traveling the length of the scale.

If we have the free streaming scale larger than the Jean's scale, nothing will form in the Jean's scale, as particles does not talk with each other and thus the features are smeared out. Utilizing this fact, it is possible to set a boundary of how fast the dark matter are moving. [11]

4 Nucelosynthesis

Deuterium were produced in the first 3 minutes, and knowing how much Deuterium were created is very important to understand early universe, since they were produced in a very short time, and is essential for production of Helium.

However, Deuterium can be destroyed in stars later on during fussion reactions. Thus, if we find a very early quasar, and measure it's Deuterium, we should see something relatively close to the situation of the big bang production of Deuterium.

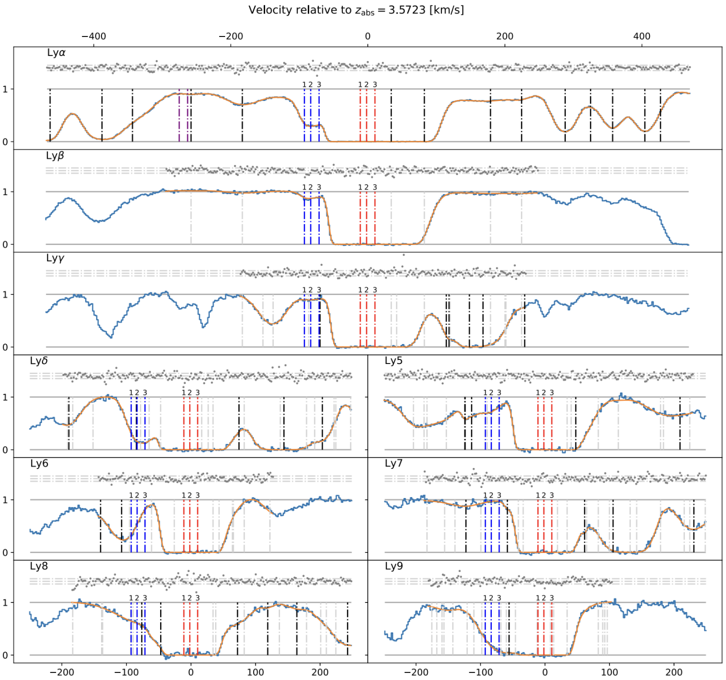

Figure 4: Spectrum of PKS1937-101. Red is Hydrogen, Blue is Deuterium. By comparing there intensity we see the amount od Deuterium produced right after the big bang. [5]

The results on D/H ratios were (The current work is the one shown above) is of the order 10^{-6}.

5 Ultra Light Dark Matter!

Since I have been working on ULDM for the past two years, the lyman-alpha forest can also place a lower limit to the ULDM mass. As we can figure out roughly the size of the Hydrogen blobs, and we want our bosonic ULDM (They have to be bosonic since they are too small and share a huge debroile wavelength. Their matter wave will occupy the same space with each other, and Pauli does not allow that to be bosonic.)

Now consider the De Brogile Wavelength of a Dark Matter:

$$\lambda = \frac{h}{p} = \frac{h}{mv}$$

Here v is the viral velocity of the standard halo model.

Then if we have a tiny p, the λ would be huge. Think of these mass as waves, and recalling the sampling principle of requiring higher frequency to reconstruct a lower frequency signal. Shannon basically said that you need at least 2f points to carry a signal with frequency f. Applying to this situation, you cannot have any meaningful structure with waves of wavelength smaller than the scale of such structure, that is $l < \lambda$. As we get the size of the blobs, namely l, from the Lyman-alpha forest, we then look into how large these blobs are, and then draw a limit to the minimum possible mass of dark matter.

6 Conclusion

The Lyman-alpha forest carries information of the universe at high red shift, bring us information of the cosmos long time ago. By looking at the red shift, depth, width, and other features of the

Lyman-alpha forest, we are able to take a peak into the early history of the universe, and how it has evolved through time. It also, by revealing the grand structure of the universe, inspire us about the nature of mass in this universe, helping us constraining the temperature and mass of the dark matter. In the future, the Lyman-alpha forest, as well as other forest-like spectrum is believed to bring us more fascinating discoveries of the universe.

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