Lyman-Alpha Forest: Features, Detection Scenarios and Simulations

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Abstract. The Epoch of Reionization (Eop) is a very important period which helps understand the evolution and formation of our universe. The Lyman alpha emission from the highly red shift quasars provides us information of the universe during the Epoch of Reionization. The Lyman alpha forest is the spectra of the Lyman alpha emission in the spectra of quasars with high red-shift. Intergalactic medium (IGM) causes the absorption lines in the spectra. The study of Lyman-alpha forest and the Epoch of Reionization has been an been a important topic in cosmology since Gun and Peterson first detected the absorb line in the spectra of quasars. This passage wil first discuss about the formation of Lyman-alpha forest and discusses the features Lyman alpha forest and the information indicated by these features about the universe during the Eop. In the last part, this paper summarizes the detection approach of Lyman alpha forest and the simulation of IGM in EoP. These results shed light on guiding further exploration of Lyman Alpha Forest.

Keywords: Lyman Alpha Forest; Epoch of Reionization; Simulation; Detection Approaches intergalactic medium.

1. Introduction

Lyman alpha Forest is a famous topic in cosmology. That is the only direct method to observe the properties of IGM. The Epoch of Reionization is a very important period during the evolution of the universe. After the Big Bang, all the matter in the universe was ionized, and as the universe expanded, the temperature dropped and the electrons combined with protons. During this time, the universe is totally neutral, and the photos can't travel in the universe, so the universe is total "dark". Then, the early galaxies and quasars formed in the early universe, and the radiation from them heated the matter around then.

This causes the neutral hydrogen ionized against, and this period of time is called the Epoch of Reionization (EoR). There were lots of expanding bubbles containing ionized bubbles in Epoch of Reionzation, and the universe today is in a state which all is totally ionized in large scales. When the light of the quasar travels in the universe, it will be absorbed by the general intergalactic medium, and then people will find many absorption line on the spectrum of Quasar, and that is the Lyman alpha forest. The Lyman alpha forest provides us lots of information about the intergalactic medium in the Epoch of Reionization. Contemporarily, as the development of the computers, people started to simulate the evolution of the universe, and that provide us a new perspective to study the universe. The simulation can help us get direct information about what is going on in the universe at different epoch. Many significant results have been got by study the Lyman-alpha forest with traditional detection method and computer simulation. In 1965, Lyman alpha forest absorption in a QSO spectrum was first observed and recorded [1]. An emulator has designed for the Lyman-α forest 1D flux power spectrum [2]. It has become the basisi of the state-of-art scenarios that the Lyman alpha forest is a natural consequence o arising in ΛCDM models [3].

This paper will first discuss about some basic features of the Lyman alpha forest spectrum. These feature shows important physical features of IGM during the early universe, such as the temperature, column density, size and ionization state of the Lyman alpha forest clouds. This research will introduce the method which derive the physical properties from the features in the Lyman alpha forest spectrum, and discuss the basic physical principles which lying behind behinds these features. Then, the article will discuss the observational method of the Lyman alpha forest. This paper will introduced how the detection scenarios develop from 1965, when people detect the Lyman alpha forest for the first time up to now. With more advanced equipment and new method, people has the spectrum forest with higher resolution and people can observe the QSO with higher red-shifts which can provide the information closer to the origin of universe. Finally, this paperwill discuss about the simulation of IGM, including the simulated method, several important simulation programs and the results these simulation indicated. Afterwards the advantages of the simulation and the reason how it help this paper get deeper understanding of the Lyman alpha forest spectrum will be explained. In addition, this study will also discuss about the lack of these simulation and some improvement, which will be carried out and achieved in the further research.

2. Descriptions of Lyman-α Forest

Typically, the wavelength of the Lyman-alpha emission is 1216 angstrom which is in the ultraviolet band. During the Epoch of Reionization, most of the radiation is the Lyman-alpha forest, because most of the matter is hydrogen. Quasars are extremely luminous AGNs [4], which are very far away from us. Most of the observed quasars have a redshift a greater than 4, and the quasar is just a light dot in the telescope. Since people can't identify the spatial structure of it, when people first found the object, they thought that is a star. After they analyzed the spectra of Quasar, they found that the spectra is very different from that of the stars. Subsequently, mankind knew that quasars is actually galaxies formed in the early universe far away from the earth. Since, QSOs are very far away from us, one can only observe one lines-of-sight from it. However, in some special cases, such as teh gravitationally lenses QSOs, one can observe two lines-of -sight of it, and it can help to calculate the size of the cloud. By observing different Quasar, people can obtain the Lyman-alpha Forest at different red shift. A debating problem about the evolution of the Lyman-alpha forest at different red shift is still discussing [5].

3. Features

3.1. Width of the Spectrum Lines

The spectra of the atom should have several certain wavelength, so one should get single straight line in the Lyman alpha forest ideally. However, the absorption line actually have width. The width of the spectrum lines is a measure of the total velocity distribution in the gas both microscopic velocity and macroscopic velocity. All the particles are in continuous random motion, so at a certain time, some of the atom move away from the observer and some move towards the observer, and according to the Doppler Effect, the wavelength will shift, which broadens the absorption line. Moreover, the macroscopic motion, such as Turbulence, Bulk flows, and broadening of an extended object by Hubble expansion, will also influence the width of the absorption line.

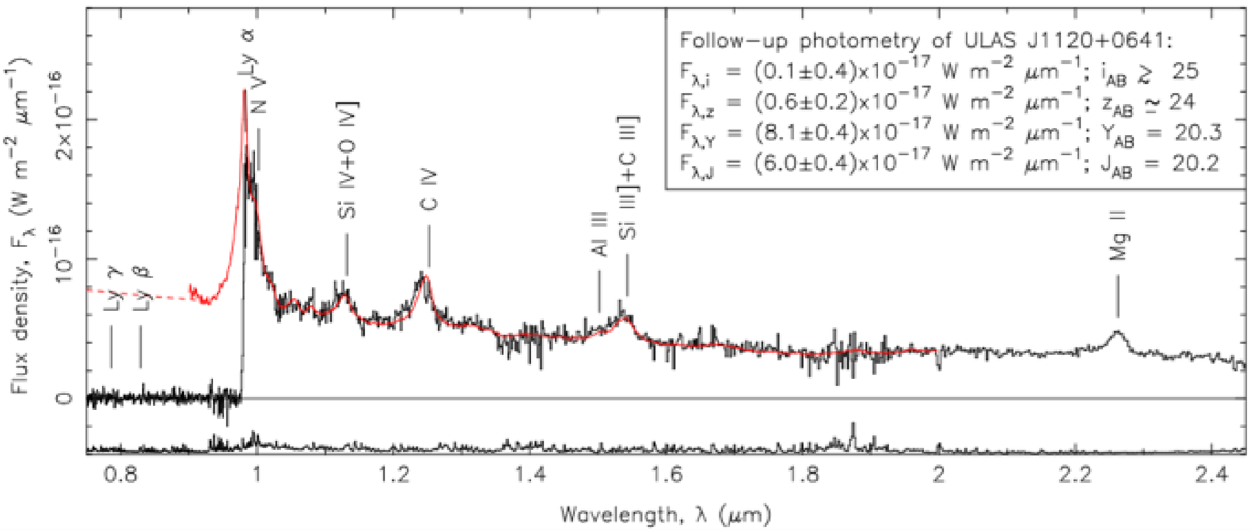

Fig. 1 The spectra of Lyman gamma and Lyman belta

3.2. Column Density

In fact, one can define X as the number of absorption lines, and define N as HI column density. By studying their relationship, it tells us the probability for a line-of -sight of QSO to intersect a cloud having given column density N. The distribution can be well-parametrized by the following function:

$$\frac{\mathrm{dX}}{\mathrm{dN}} \propto N^{-1.5} \tag{1}$$

The range of N varies from 10^{12} to 10^{22} m^{-3}.

4. Detection Approaches

Scholars obtain the Lyman alpha forest by detecting the QSO with different red-shift. When the light travel forms the QSO to the detection equipment, it will be absorbed by the clusters and that caused the formation of the absorption lines The red-shift number of observed QSO has a very large range, which both contain high-redshift quasar (z>3) and low red-shift quasars (z<1). As shown in Fig. 2, these spectra are the Lyman alpha forest of quasars with different red-shift number. After the red-shift caused by the expansion of the universe, the Lyman alpha series transferred to visible light and infrared light. This band of light isn’t likely to be absorb by the atmosphere of earth so the spectrum can be detected by the equipment on the earth.

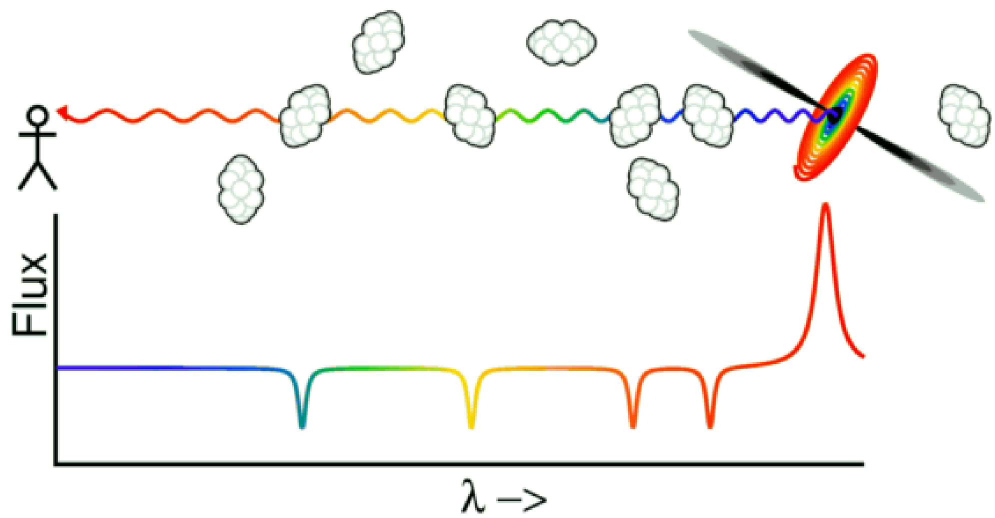

Fig. 2 Detection of Lyman alpha forest

One detection approach which was used to identify the size and distribution of Lyman alpha absorbers is Probing adjacent sightlines [6]. By observing close lines-of-sight to groups pf QSOs and comparing the flux-power spectrum from different QSOs, the size and geometry of absorber clouds can be estimated. As shown in the Fig. 3, some QSOs' light will pass through the Lyman alpha absorber and others won't be covered by the absorbers, and this creates difference in the absorption lines in the spectrums. From these different spectrums, the general disruption of the Lyman alpha absorb can be estimated.

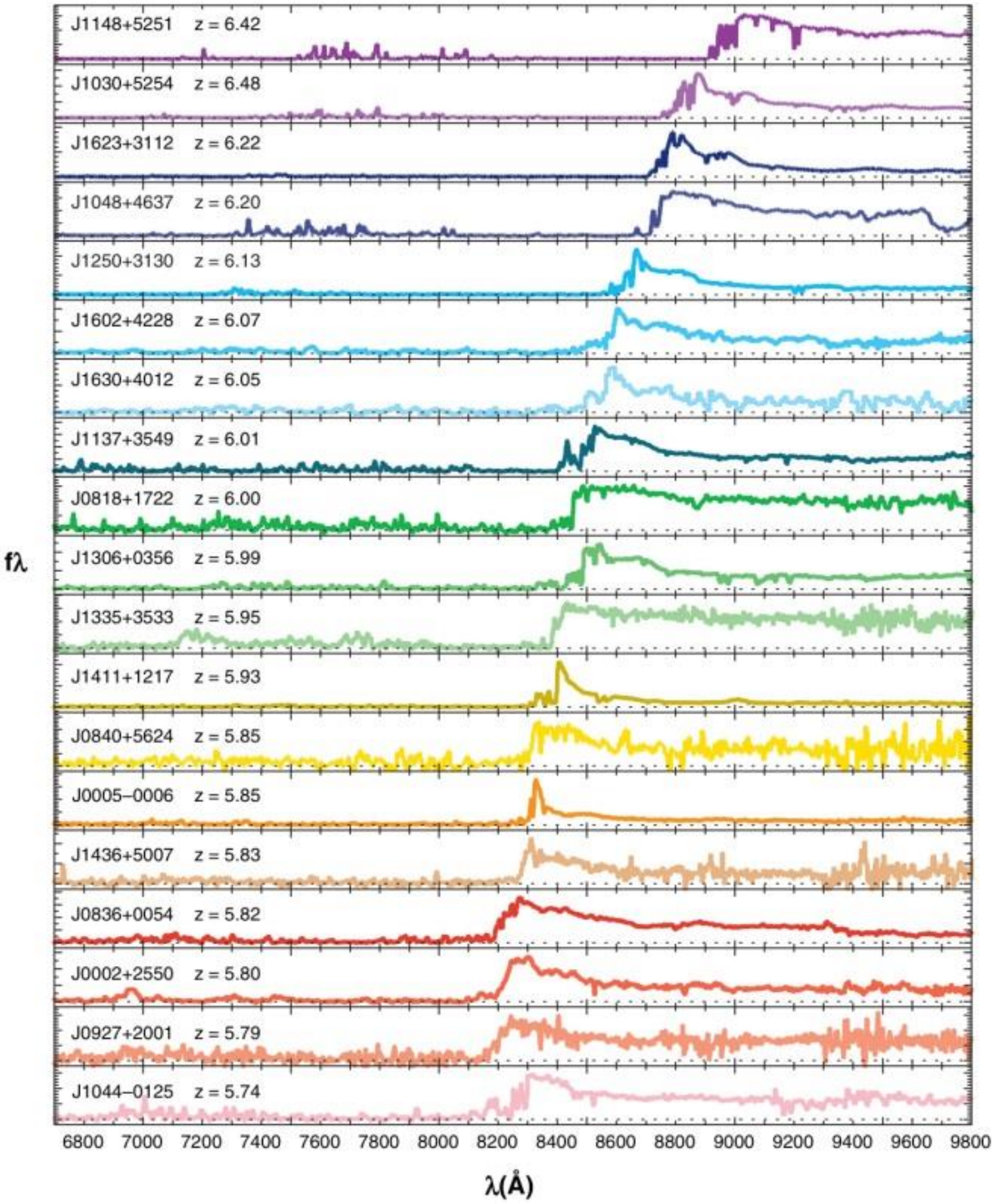

Fig. 3 Lyman alpha forest with different redshift.

5. Simulations

There are two physics model of the Epoch of Reionization. The first model is the Pressure-confinement model. However, the result of this model contradicts the observational evidence.

Another model is the Cold Dark Matter Model, in this model, the universe was dominated by large amount of cold dark matter (CDM). This cold dark matter doesn't emit thermal radiation itself, and it interact with other matter by gravity. In this model, the IGM will become structure like filament and sheet. The result of the Cold Dark Matter Model agrees with the observational evidence [7]. THESAN project is a suite of large-volume cosmological radiation magnetic-hydrodynamic simulation of Epoch of Reionization. One key science area of THESAN project is using Lyman alpha forest to study the IGM. THESAN allowed us to study the onset of dispersal areas in Lyα forests. These features are produced by a single bright galaxy and therefore need to include the state-of-the art model of galaxy formation one use here. The rarity of these features at high redshifts and the patchy nature of the reionization process require large simulation volumes in order to correctly capture statistical changes in IGM properties. Moreover, recent observations suggest that IGM optical depth profiles are difficult to reproduce in standard EoR models. It is interesting because it is the first step in moving beyond a global average measure of IGM properties. Many different mechanisms have been proposed to reconcile the observed and predicted distributions, but the scientific community has yet to reach a definitive answer. THESAN allows us to investigate this further and provide a reliable prediction from a full physics state-of-the-art set of simulations [8]. As illustrated in Fig. 4, the gas during EoP is arranged in filaments and sheet, and this structure is "cosmic web" [9, 10].

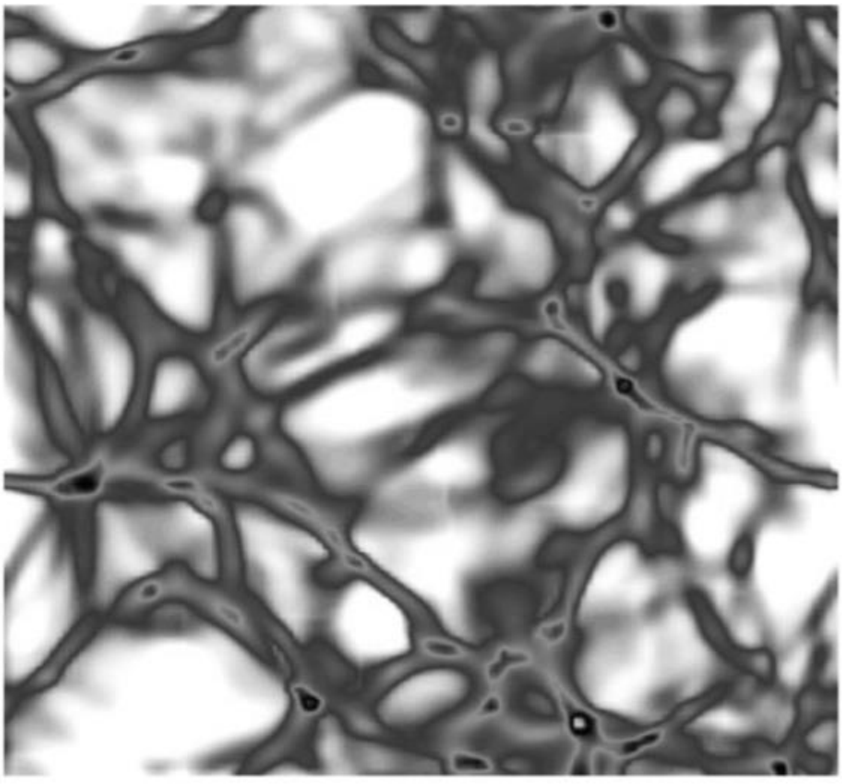

Fig. 4 simulation of IGM in EoP

6. Limitations & Prospects

The understanding of the Lyman alpha forest and the Epoch of Reionization is still not enough. As the development of detection technology, Lyman alpha forest with higher resolution can provide more information about the size, density and ionize state of the IGM in the early universe. Moreover, the more advanced telescope can observe the quasars with greater number of red-shift, which means it can observe the earlier universe. The James Webb Space Telescope can detect the band of infrared light and look deeper into the universe. It can help the detect the quasars formed in the very early and make us learn more about the Lyman alpha forest. The simulation also develops very rapidly. However, the simulation still has many limitations. The simulated volume is still relatively small, and there are still many physics factors not included in the simulation. The future simulation will contain improved and complete physics models and more powerful ability of numerical realization.

7. Conclusion

In summary, this paper investigates Lyman-alpha Forest based on detection approach of quasar spectra and modern simulation of universe evolution. Specifically, the physics properties of the universe in Eop drawn from the features of Lyman alphas forest. According to the analysis, the width of the absorption lines reflects the velocity distribution in the IGM gas. Moreover, one found a regulation of column density drawn from the statistical study of Lyman alpha forest spectrum. Besides, this paper introduces the basic principle of detecting the Lyman alpha forest. In addition, this paper introduces a way to identity the geometry of the absorbing clusters. Nevertheless, the simulation physics model, THESAN project, an important simulation projects were introduced. In the future, the advanced detection technology and the developed simulation with additional physics and more ambitious numerical realizations will provide us more details about Lyman alpha forest. Overall, these results offer a guideline for Lyman alpha forest and future study of the formation of early universe.

References

[1] Gunn J E, Peterson B A. On the Density of Neutral Hydrogen in Intergalactic Space. The Astrophysical Journal, 1965, 142: 1633-1636.

[2] Bird S, Rogers K K, Peiris H V, et al. An emulator for the Lyman-α Forest. Journal of Cosmology and Astroparticle Physics, 2019, 2019(02): 050.

[3] Bolton J S, Puchwein E, Sijacki D, et al. The Sherwood simulation suite: overview and data comparisons with the Lyman α forest at redshifts $2\leq z\leq 5$. Monthly Notices of the Royal Astronomical Society, 2017, 464(1): 897-914.

[4] Wolf C, Bian F, Onken C A, et al. Discovery of the most ultra-luminous QSO using GAIA, SkyMapper, and WISE. Publications of the Astronomical Society of Australia, 2018, 35.

[5] Fan X, Carilli C L, Keating B. Observational constraints on cosmic reionization. Annu. Rev. Astron. Astrophys., 2006, 44: 415-462.

[6] Elowitz R M, Green R, Impey C. Probing Correlations of Lyman alpha Forest Clouds. American Astronomical Society Meeting Abstracts. 1992, 181: 79.10.

[7] Viel M, Becker G D, Bolton J S, et al. How cold is cold dark matter? small-scales constraints from the flux power spectrum of the high-redshift Lyman-α Forest. Physical Review Letters, 2008, 100(4): 041304.

[8] Kannan R, Garaldi E, Smith A, et al. Introducing the thesan project: radiation-magnetohydrodynamic simulations of the epoch of reionization. Monthly Notices of the Royal Astronomical Society, 2022, 511(3): 4005-4030.

[9] Structure and Evolution of the Intergalactic Medium from QSO Absorption Line Systems. Atlantica Séguier Frontières, 1997.

[10] Li M, Pan J, Gao L, et al. Bulk flow of halos in ΛCDM simulation. The Astrophysical Journal, 2012, 761(2): 151.