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Implications of IGM Physical Properties on Galactic Overdensity During the Late Reionization Epoch

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Abstract:

The reconstruction of the image of the epoch of reionization has been a broadly investigated topic, focusing on unveiling correlations between numerous factors. Yet these correlations are not clearly defined in different scenarios, while the correlations between important physical properties of the intergalactic medium (IGM) and local galactic overdensity could be interpreted as indications of the history of the rapid epoch of reionization at $z = 68$. This paper investigates the correlations between galactic overdensity and IGM sightline opacity and lyman-α transmitted flux. While using observational evidence from various sources, including quasar lyman-α emission and sampled observations of galaxies, results from hydrodynamic simulation suites are also utilized extensively in providing detailed data samples. The direct correlation between the aforementioned factors and the reionization bubble theory is formulated and proposed as a potential generalization. However, there are limitations in refining the formulated theory. An insufficient level of proof and applications is examined. This work will benefit similar areas by providing potential applications for the investigation of galaxy evolution and the formation of macroscopic celestial structures, allowing extended theories and correlations to be conceived and applied.

Keywords: Epoch of Reionization, Intergalactic Medium, Lyman-α Forest, Sightline Opacity

1. Introduction

The Intergalactic medium (IGM) is the gaseous substances that is distributed across the universe, filling the space between the galaxies and other celestial objects. It consists mostly of ionized hydrogen with a small portion of helium and baryonic matters. As the dominant component of the universe by volume, the IGM is not only a major reservoir of matter but also a record of cosmic evolution. It physically interacts with galaxies and quasars, preserving critical evidence of key historical events through its intrinsic

physical properties.
The Epoch of Reionization (EoR) happened around z ~ 6 to 14. This epoch marks the final major phase transition of the universe, during which the IGM was reionized by the first luminous sources (e.g., stars and galaxies). Consequently, many of its key physical properties were permanently altered. Mapping projects have been reconstructing the end of the Epoch effectively [1, 2], demonstrating the physical properties of IGM throughout the age of reionization from redshift range 4 ~ 6. Other projects that are dedicated to map the evolution of IGM throughout the EoR also made significant results on describing the characteristics of IGM in vast time periods [3]. Conversely, the properties of IGM in the EoR is mostly determined by factors of galaxies that are forming and reionizing it. Therefore, it is possible to imply the characteristics of the environment that the IGM is in through the properties of IGM throughout different redshift ranges. Such inferences can enhance people's understanding of early galaxy formation and the development of the cosmic web, potentially providing evidence or methodologies to explain the properties of present-day galaxies.
This paper will investigate the relationships between local galaxies' characteristics and the physical properties of IGM in the EoR to theorize their connections. Computer simulations from various projects will be employed as the major methodology to provide data, associating with applicable observational evidence. This paper builds on top of various papers on related topics that incorporate sections of simulation data collection and theorization of similar subjects and processes, while an attempt of exploration on macroscopic connections will be made. An analysis on the data provided by public samples of spectroscopy and JWST will also be conducted to notify the correlations of lyman-α (lyα) forest with other factors [4,5]. The paper is organized as follow: Section 2 discusses the methodologies that the theories build on; Section 3 elaborates the results; Section 4 and 5 finish the discussion and provide conclusion.

2. Methodologies

The behaviors and properties of the intergalactic medium (IGM) could be inferred from the computer simulations of the age. Due to the limited access to the simulation model itself, this paper will mainly adopt results from various presentations on the simulation. Depending on the results adopted, other various simulation suites will be utilized. An important simulation suite is the THESAN Project, which is competent in simulating the morphology of the process of reionization. It is a suite of hydrodynamic simulation of great capability, where a high resolution on baryonic matter of $5.82\times106M_{\odot}$ is combined with a large volume (Lbox=95.5 cMpc) to enable the model to be able to conduct high-quality hydrodynamic simulation. Although it has been noted that the simulated resolution decreases over tens to hundreds of Mpc, this limitation is less critical for macroscopic data collection due to constant re-sampling at large separations 2. Nevertheless, the THESAN project remains effective in depicting structures within ~ $32h^{-1}$ Mpc, providing a sufficient range of data for robust inferences.
Spectroscopy data on lyα forest will also be utilized to provide basis to understand the correlation. A full dataset of high-resolution QSOs spectra in late EoR from the E-XQR-30 quasar sample generalized from the XSHOOTER spectrograph obtained by ESO Very Large Telescope (VLT) [4]. A relatively large amount of sample size (294) of galaxies are picked in a limited redshift range (z = 5.8 ~ 6.6). Results using Spectroscopy of the lyα forest will be based on Ref. [4] where similar parameters of assessment will be adopted. Datasets from JWST/NIRSpec Spectroscopy (NIRSpec) will also be utilized to visualize the lyα forest distribution over five sample fields in celestial coordinates, providing observational evidence for theories in correlation of the examined factors [5]. These JWST data will be particularly valuable for inferring correlations on larger scales [d > 15 h^{-1} Mpc] and at higher redshifts (z > 7). For detailed descriptions of the methods, the author refers the reader to Ref. [4, 5].
To match the spatial relationships between IGM opacity and galactic overdensity, the author will quantify their correlation as a function of distance from a designated sightline, following the conventions of the respective databases used.

3. Synthesis of Results

3.1 Correlation in Factors

From all the possible factors that affect the process of reionization, the factor of galactic overdensity in local reionization is essential in assessing the results of simulation. While the physical parameters of the lyα forest is dependent on the local distribution of galaxies, other visual factors of the galactic IGM could also be derived from its relationship with local recognizing galaxies. Galactic overdensity can be probed over large distances from a sightline (up to d ≈ 5 h^{-1} Mpc), where it serves as an important factor influencing the overall efficiency of reionization and the physical state of the IGM at various stages. Therefore, in this section, the correlation between the various factors of the IGM and the galactic overdensity

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will be discussed exclusively. All results discussed in this section are ranged from z = 5.5~8, which precedes the end of the Epoch of Reionization (EoR), unless explicitly stated otherwise. All statements in this section are developed upon referenced data sets and figures.

Sightline opacity, typically measured by the lyα transmission flux or the lyα effective optical depth (τ_{eff}), is a crucial metric for determining the physical state of the IGM during the EoR [6,7]. Researches have been consistently correlates it with the factor of galactic overdensity. By setting the function of sightline opacity with the variable of distance from the sightline. In Ref. [8], the sightline opacity is measured in directly correlation with galactic overdensity, presenting different trends in controlled sightline opacity: In extreme sightline opacities with less UVB as defined by the paper, galactic overdensity tends to be positively correlated within the range of 72 h^{-1} Mpc (z = 5.7); while for moderate opacity, the galactic overdensity tends to be spreading out, presenting an evenly spread pattern.it is suggested that for opaque sightlines, opacity is negatively correlated with galaxy density at close distances (d < 15 h^{-1} Mpc) but positively correlated with galaxy density at larger distances. For transparent sightlines, a positive correlation with distance is reported. Other research using different models and methods has found similar trends [9]. However, the greatest disagreement among studies concerns the impact of galactic overdensity in the immediate vicinity of the sightline (very small d).

The factor of lyα emission is also included in the examination. It is also intricately linked to sightline opacity, a connection that will be elaborated upon in the following sections. People investigated high lyα emission (EW > 100Å) galaxies and placed them in visual coordinates and grouped in redshift range of z = 7.0 ~ 7.6 and z = 7.6 ~ 8.5 [5]. By classifying the galaxies visually, it successfully reconstructed the environment centered the overdensed regions and concluded with matching to the reionization bubble theory. Some work elaborated on the details of the trends and preciseness in the data sets of lyα emission with data sets from quasar samples [1,4]. After corrections, the lyα transmitted flux presented a steady increasing rate, signifying the rate of reionization over the redshift ranges. Altogether, the sources made an agreement on a trend of rapid reionization.

3.2 Implied Physics From Sightline Opacity

In Fig. 1, By comparing the observed correlations with the evolution of these properties as a function of redshift, it is possible to match two scenarios, opaque and transparent, to the early and late stages of the EoR. These also suggest their distinct physical implications for their surrounding environment, both locally and globally.

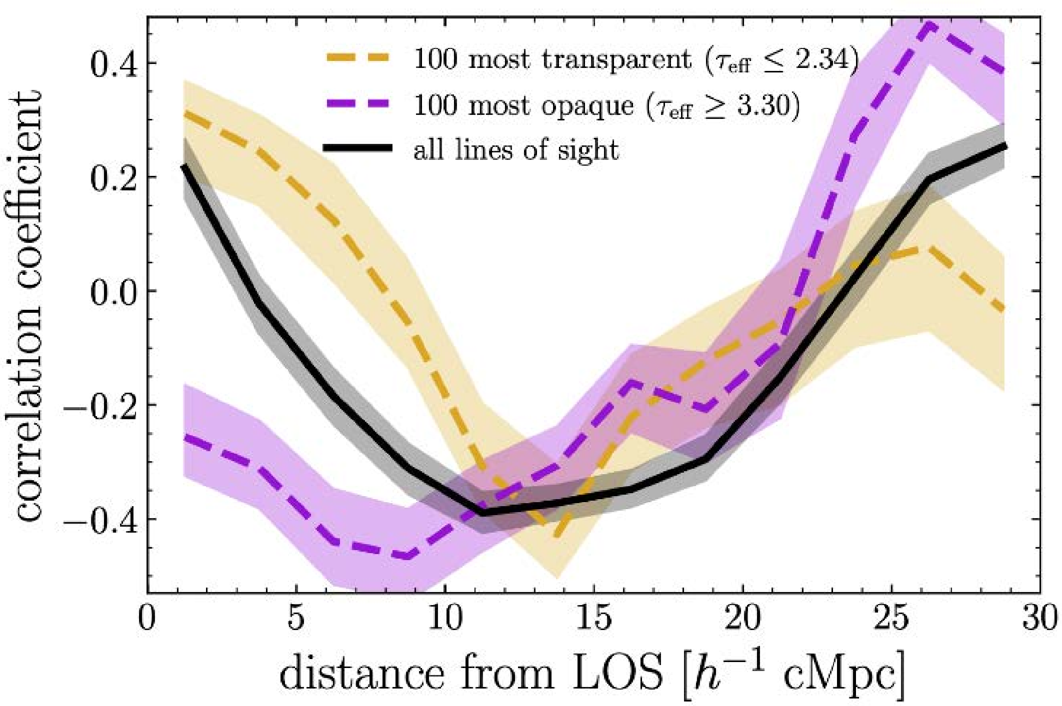

Fig. 1 Correlation coefficient of galaxies on sightline transparency in distances [6]

Firstly, focusing on the correlations at small scales, the progression of reionization in a local region is influenced by the relationship between local overdensity and optical depth. This relationship can be interpreted using simulations that track the evolution of density and ionization state. The transparent scenario suggests that it has a larger galaxy and gas density, lower temperature, and a lower H I fraction, as indicated by the simulation results within the range of 5 $\lesssim$ d/[h^{-1} Mpc] $\lesssim$ 20. Conversely, in an opaque scenario, where one region could have lower optical depths, one could see from the graph that for galaxies closer to it (d/[h^{-1} Mpc] $\lesssim$ 7), they had larger masses and were ionized first (z) than in the transparent scenario. This suggests that in an opaque scenario, galaxies closer to the sightline complete reionization first, whereas in a transparent scenario, galaxies farther away from the sightline complete reionization first. Consequently, the opacity from a sightline is dependent on when its nearby galaxies reionize. If the observed sightline is more opaque, local galaxies' reionization is more likely to originate from the sightline region (inside-out). If the observed sightline is more transparent, local galaxies' reionization is more likely to originate distantly (Outside-in).

The corresponding trends to the sightlines could explain the previously demonstrated negative correlation between the galactic density and the opacity in short distances in the opaque scenario. Overdensity in the local region would theoretically help with the process of reionization. However, overdensities of the lower-mass galaxies could shield the region from being reionized. This might be due to the fact that these locally ionized galaxies geometrically blocked UV photons from more massive, external galaxies that had a greater capability to reionize the region. Additionally, frequent recombination events, resulting from the high density of the overheated IGM, could further maintain a high neutral fraction. These effects overcome the effect of local overdensity and result in the negative correlation, for $d \lesssim 7h^{-1}$ Mpc in distance to the sight line in the opaque scenario. These explanations fit the expected Galaxy-lyman-α Cross-Correlation (GaLαCC), turning out to be substantialized. The trends could demonstrate the correlation between observed sightline opacity with global reionization trends: an opaque sightline may represent a region in the early stages of local reionization, while a transparent sightline is more indicative of a globally advanced stage of reionization.

Developing from previous results, it is possible to extend the theory to across the redshift range by combining it with results from lyα emission data. By identifying and differentiating the respective environments that strong and weak lyα emitters are in, their correlations will be discovered and quantified.

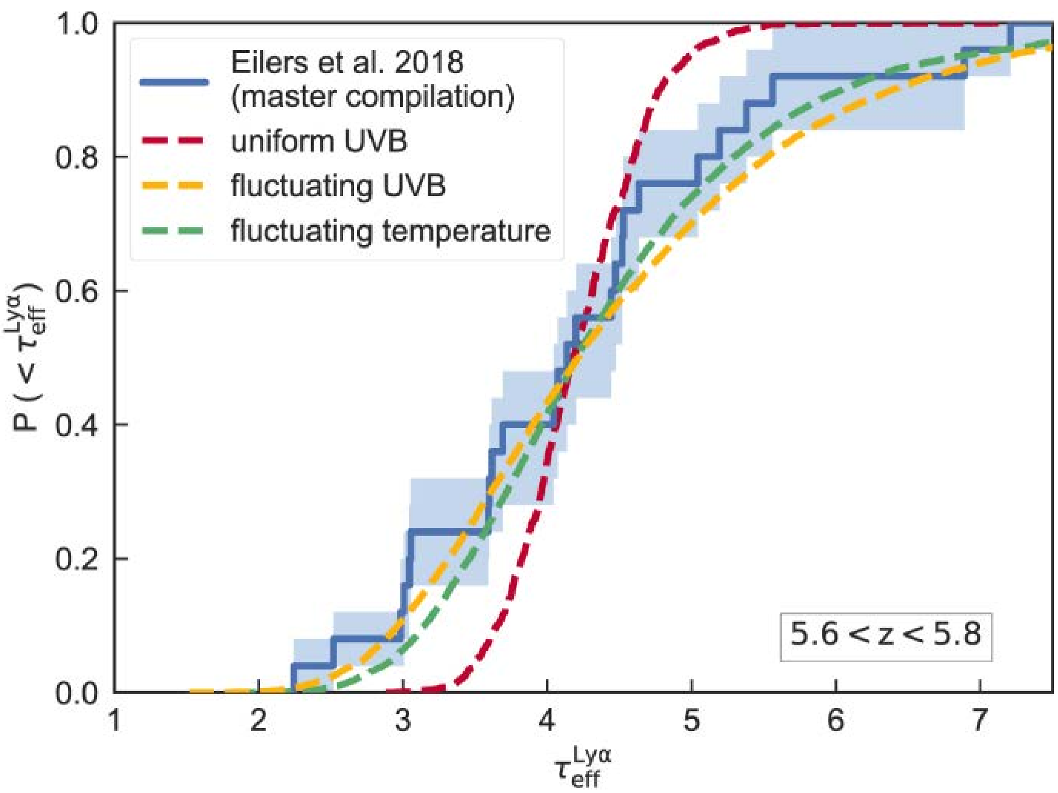

Fig. 2 Cumulative distribution function of Spectrum percentage and opacity [1]

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Developed upon Fig. 2, an inference on the surrounding environment of strong lyα emitters could be made. The figure presented the strong lyα emitters and the associated reionization bubbles, most likely indicating the trend of patchy reionization over the early EoR [5]. It is also suggested that the overdensities typically spans as much as the identified bubbles are. Therefore, a correlation between the span of a constant overdensity and the reionization bubbles could be determined. The statement of assumed correlation may suggest that while the level of overdensity is remained constant, its span is positively related to the reionization bubble which could be interpreted in terms of the lyα transmitted flux. The span is negatively correlated with the reionization bubble when there is extreme overdensity over short distance. As this correlation applies, it could effectively support the aforementioned correlations. With a region of mild overdensity combined with a larger radius, it will effectively reionize the region, resulting in high level of lyα transmitted flux. On the other hand, a region with a smaller reionization bubble will be able to reionize nearby region most effectively while unable to expand the bubble with the reason aforementioned. It requires the intervention of other bubbles to expand, presumably a cause of the assumption of a large reionization bubble that made of three regions of respect overdensity, which could explain the previous discovered strong positive correlation between extreme opaqueness and nearby galaxies ($d < 15\ h^{-1}$ Mpc). In general, the history of EoR could be correlated and limited by the demonstrated factor.

4. Discussion

In this paper, the author discussed about the underlying correlations of the lyα emission and sightline opacity with local galactic overdensity. Utilizing current observational data and simulation data about the lyα transmitted flux and sightline opacity, it is possible to backward propagate and inference a reasonable speculation about the local galactic overdensity. On the other hand, it implied important characteristics of the trends of the formation of the reionization bubble over the period of rapid reionization by considering the factor of distance from the sightline. Comparing the correlations directly to the trends of reionization, the history of selected local overdensity could be implied and rationalized. Furthermore, it could be interpreted more broadly in to the rapid epoch of reionization (EoR) with $z \sim 6$. While the universal structures of the universe mature, the model applies to certain situations. Referencing to different simulations models of EoR, the period of rapid reionizing matches generally by inference with physical principles [3,7]. Observational evidence on quasar sampling also fits the model with generalized trends in data sample.

There are certainly limitations to the methodologies and inferences. The correlation was solely derived upon simulation model data support and observational evidence, which were utilized effectively and extensively in the analysis, resulting in a purely theorized correlation referencing to utilized simulation parameters and observed phenomena [4,6,10]. Developing from the correlations, its connection to the reionization trend is also not consolidated with data support and observational evidence, where only literary statement is provided upon the implied correlation. In the future, the correlations should be consolidated with more intentionally measured data and direct calculations that is intended to induce the desired results. On the other hand, the limited sampling size also constraints the current effort in interpreting the data. In various cosmological simulations, types of mass interactions could be involved, such as in the situation of dark matter simulation, which contributes to the important factor of galactic structures and IGM properties. Limited data sets on the factor of distance are used for the construction of the correlations, where important connections to the trends of reionization is directly related to the factor of distance utilized to consist the data. This might result in the incorporation of more errors in measuring the correlations between the factors, resulting in deviations over specific ranges measured in h^{-1}Mpc. The other factor to consider is overdensity and the reionization bubble, where two were weakly related under multiple scenarios of speculations.

5. Conclusion

With above sections, key correlations and speculations are inferred and explained, providing a possible theory in relating the factor of galactic overdensity and opacity with the trend of rapid reionization ($z = 6 \sim 8$). While the galactic overdensity is negatively correlated with the sightline opacity, it is dependent on the distance at the early stages of reionization, directly relating to the reionization bubble as indicated by the lyα transmitted flux. The author also discussed the validity of the results and potential areas for improvements. In addition, some potential applications of the implied correlation is also discussed upon available data. Looking forward, several topics is worth of further investigation. The first one is the history of dwarf galaxies. These galaxies typically have significantly smaller number of stars associated with lower luminosity. Some of the dwarf galaxies are ancient, consisting valuable information of the late reionization epoch. By applying the discovered correlations, it is possible to reconstruct the evolution of the parameters in measuring the physical characteristics of dwarf galaxies with examinations on the physical properties of IGM within its local region of overdensity. Another realm of application is to derive evolution of the current cosmic web structure. By relating the cosmic web structure with regional parameters of aforementioned physical properties, it is possible to derive the reionization bubble in relation to the local overdensity and lyα transmitted flux, then speculate on the universal structures on a macroscopic scale.

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