Analysis of the Principle and Simulations for Re-ionization of THESAN

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Abstract. The re-ionization era was always mysterious to humans, because of its great time distance. It is the period when galaxies form due to dark matter congregating and emit high energy photons ionizing the surrounding (entire) universe. The THESAN simulation is a successful program that uses computers and models that simulates what happened in the re-ionization era. However, this is a complex program that contains multiple research directions, the aim of this paper is to summarize the work of the THESAN team giving first a background information about simulations, the re-ionization era, and certain models for re-ionization era. Then, this study introduces the THESAN model which contains three important parts of radiation, galaxy formation, and cosmic dust. Afterwards the results of the simulation such as Lyman alpha emission will be summarized and observation methods such as 21 cm line will be illustrated. At last, there will be discussion of the limitations of the THESAN study and its future outlooks majorly focusing on the use of JWST detection abilities on the THESAN simulation.

Keywords: THESAN project; simulation; epoch of re-ionization.

1. Introduction

In the development of physics, experiments have played a essential role in parts such as calculating a constant or testing a hypothesis. Experiments such as the Young's double slit experiment or the Michelson-Morley experiment have all contributed greatly to physics development. However in cosmology, due to the large timescales, distances, and magnitude experiments with controlled variables can not be performed. For example the formation of galaxy has a great magnitude, the reionization era has a great timescale. In this case the only resource people can obtain in this situation is passively collected data from observatories using telescopes or other devices, which can not fulfill all requirements. Modern cosmological observations allow us to study in great detail the evolution and history of the large scale structure hierarchy [1] and cosmological simulations of galaxy formation have been instrumental in advancing the understanding of structure and galaxy formation in the Universe [2]. These simulations based on theoretical models uses computers to calculate the process of movements, formations, and etc, providing results that are similar to what have happened in the real universe. The THESAN simulation is shown corresponding to many data that are observed in these high redshift galaxies through inferred spectrum such as the stellar-to-halo-mass relation, galaxy stellar mass function, star formation rate density, and the mass–metallicity relation [3]. Using these controlled universe where giant numbers are no longer a consideration, researchers can find out the entire process of reionization in few years or the result of a galaxy formation. With all of these data produced from all of these simulations cosmology studies can also present experiments like other studies, leading to new knowledge and theories about what have happened in the cosmos.

One famous and starting simulations is called the IllustrisTNG project which originated since 2014 by a collaboration of scientists from different regions of the world. This project aims to study the formation of galaxies using computer simulations as a tool. Through analyzing and calculating the data and graphs given by the simulation to understand the process of galaxy formations. There are different "boxes" meaning different conditions in the simulation which all gave important information for the process of understanding galaxy formation. And new simulations was also performed for example the THESAN project that will be majorly talked about later in the paper. The THESAN project is designed to provide a comprehensive picture of the emergence of galaxies in a full reionization context [4]. This project is more mature than models before, it updating it with new algorithm. It also adds on new methods combining state-of-the-art galaxy formation (IllustrisTNG) and dust models with the AREPO-RT radiation-magnetohydrodynamics solver [5].

The THESAN simulation is a great project filled with different researches based on one big simulation of the reionization era. Its research topics varies from predictions of high redshift galaxies to the study of intergalactic mediums through lyma-alpha forest, and etc. In addition, multiple articles are proposed on the same topic producing a great amount of results. In this paper, the goal is to give a overview of this big project summarizing its discoveries about the reionization period. First the paper will be about a basic description of the reionization period: its existence and formulas that describes it. Second of all the paper will introduce the modeling methods of the reionization period, or how did the THESAN team run the simulation. Then, it will summarize the results of the THESAN project. Then, the observations of similar high redshift galaxies that are related to the THESAN simulation for example images or data obtained from the James Webb Space Telescope. At last limitations and future outlooks of the THESAN project and then a entire conclusion of this study.

2. Basic Descriptions

After the big bang, the universe was a place fulled with hot plasma of matter and radiation. Then as a result of universe expanding the matter cools and electrons starts to recombine forming the first atoms. This was called the recombination era in which light was first allowed to pass the universe. As the universe further on evolved a structure stated to evolve under the effect of overdensities of dark matter. These structures created are the stars and galaxies. These stars and galaxies that are first created impacted the surrounding intergalactic medium. They released a abundant number of Lyman continuum (LyC > 13.6eV) radiation [3]. These radiation lead to the increase in temperature of intergalactic medium and caused the ionization of these matters. This change or phase was called the Epoch of Reionization, or EoR in short. This was the last phase of cosmic change that greatly effected what is now the universe lived in, making the intergalactic mediums high ionized again, like the period before recombination. In this period only the highly dense galaxies with there special structure and density can remain neutral due to their high recombination rates. This reionization process started around redshift z = 20 ended around redshift z =5 (150 million-1 billion years after big bang), where masses in the universe except galaxies was fully ionized into plasma state.

The standard cold dark matter model is a model that predicts and are used in the cosmic reionization analysis. This cold dark matter (CDM) theory is also known as the lambda-CDM model which is the current standard model of cosmology that tells the universe is made of three components dark energy, dark matter, and ordinary matter. To analyze the amount of hydrogen that is ionized (hii) one can calculate the it through the total emission rate by solving the equation:

$$\frac{dN_H}{dt} = S(t) - \alpha_H^{(2)} \alpha^{-3} f_{clump} n_H N_H \quad (1)$$

In this equation NH represents the entire amount of ionized hydrogen atoms. Here, $\alpha_H^{(2)}$ is a coefficient of recombination for hydrogen (for a temperature of 10^{-4}K) [6], and a in the equation is the factor of expansion in cosmic. Gas being ionized represented by clumping factor, fclump. NH is the density of atomic hydrogen in the cosmos's mean. There are certain difficulties to obtain information about the re-ionization era through the both two methods: observations and theory. There is a great amount of high redshift galaxies that are not explored.This is due to the reason that there are still observational limitations even for the Hubble Space Telescope that only found a thousand galaxy candidates between z = 6–8 and only a few at higher redshifts (e.g, [7-10]). This problem is reaching its solution with the newest James Webb Space Telescope reaching the sky. Using its strong ability of observing radiation in infrared section leading to observations of high red-shift galaxies leading to more results that will be later mentioned.

3. Models

This study will introduce the models that the THESAN team used to model and simulate the re-ionization era. The THESAN simulation is is combination of three different models which are the previous IllustrisTNG program with innovations), the new radiation transport algorithm, and a empirical cosmic dust model. Using a composition of these three models, the THESAN team models the evolution of the universe in the re-ionization era. The simulation combines many models but also has different “boxes” or simulation conditions, for example THESAN-HIGH-2 which only contains the effect of high mass halos ($>10^{10}$M) contribute to re-ionization and THESAN-LOW-2 where only low mass halos ($<10^{10}$M) contribute to re-ionization. There are also a great number of other boxes in which aside of these two. Known as the major factor of high energy photons emission, galaxies take a very important role in the re-ionization era. The team used the previous IllustrisTNG galaxy formation model and it was further advanced and brought in new algorithms to make it more suitable for the re-ionization era model. It updates the previous Illustris simulations [9] with a revised kinetic AGN feedback model for the low accretion state [10] and an improved parametrization of galactic winds [11]. This was including feedback from supernova and solar wind, evolution of nine elements, cooling associated with redshift and etc, and black hole formations. This method was proved very useful in different simulations [11].

Radiation is essential to the entire re-ionization movement. To make the RT equations solved the team employs the AREPO-RT extension of the AREPO code [11], leading RT equation’s first two moments to be solved, complemented with the M1 closure relation [11]. However due to calculation ability limits of modern computers only the ultra violet radiation range was followed and according to the following energy levels: [13.6, 24.6, 54.4, ∞) eV divided the photon energy into groups, chosen to bracket the ionization energies of hydrogen and helium. The team tracked the photon flux and density. Solving the RT equations, the research team can accurately detect the ionization of hydrogen (hi or hii) and the temperature corresponding with photo-ionization, metal cooling, and Compton cooling [11]. The cosmic dust model is the third and last piece of the entire THESAN simulation in which the model represents the dust created and destroyed during the re-ionization era. The team strengthened the former IllustrisTNG model and connected with cosmic dust to describe its state. In this model the dust is treated as property of the gas resolution elements [12], thus overlooks the motions between two dusts. Its production is modeled by the following equation and the dust is majorly produced by stellar evolution and increases from the inter stellar medium.

$$\frac{dM_{dust}}{dt} = \frac{\left(1-\frac{M_{dust}}{M_{metal}}\right)M_{dust}}{\tau_g} \tag{2}$$

The destruction of cosmic dust majorly comes from the shock and sputtering as:

$$\frac{dM_{dust}}{dt} = -\frac{M_{dust}}{\tau_{sh}} - \frac{M_{dust}}{\tau_{sp}/3} \tag{3}$$

GADGET-4 code using second-order Lagrangian perturbation theory was used to produce initial conditions, at the initial redshift of zin = 49 [12].

4. Simulation

The THESAN simulation was very successful in which it monitors status of different factors in the cosmos during the re-ionization era [12]. One of the significant successes in the THESAN simulation is the history of re-ionization starting from red-shift z = 16 to red-shift z = 5.5. In this simulation many factors were monitored showing people the process in which dark matter starts to accumulate forming galaxies, then emitting high energy photons heating the surrounding temperature and re-ionizing the surrounding matter. Then the high energy photons further on emit, causing the entire universe to re-ionize, shown in Fig. 1. One can see the patterns of re-ionization starting form the galaxies in Fig. 2.

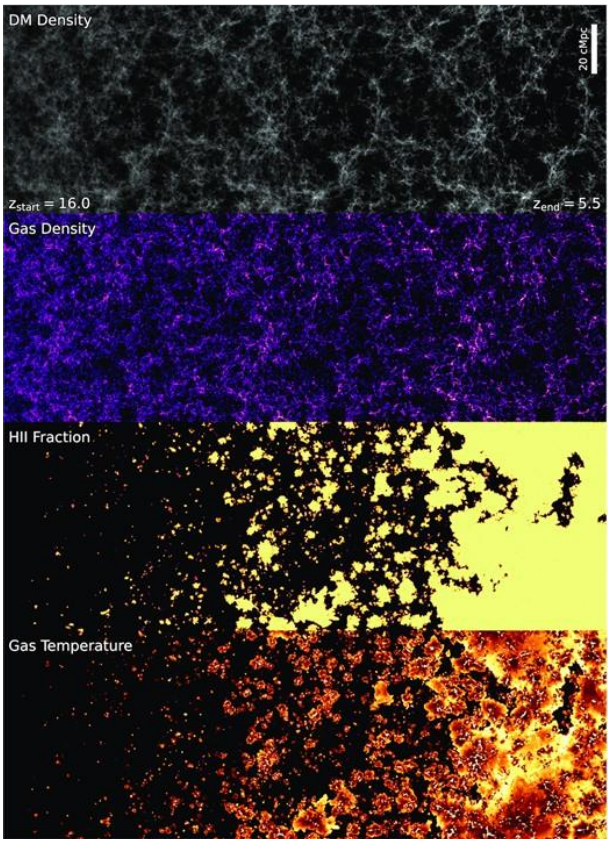

Fig. 1 A light cone of the visualization of changes in dark matter density, gas density, ionized hydrogen fraction and gas temperature in period of re-ionization from redshift z = 16 to z = 5.5.

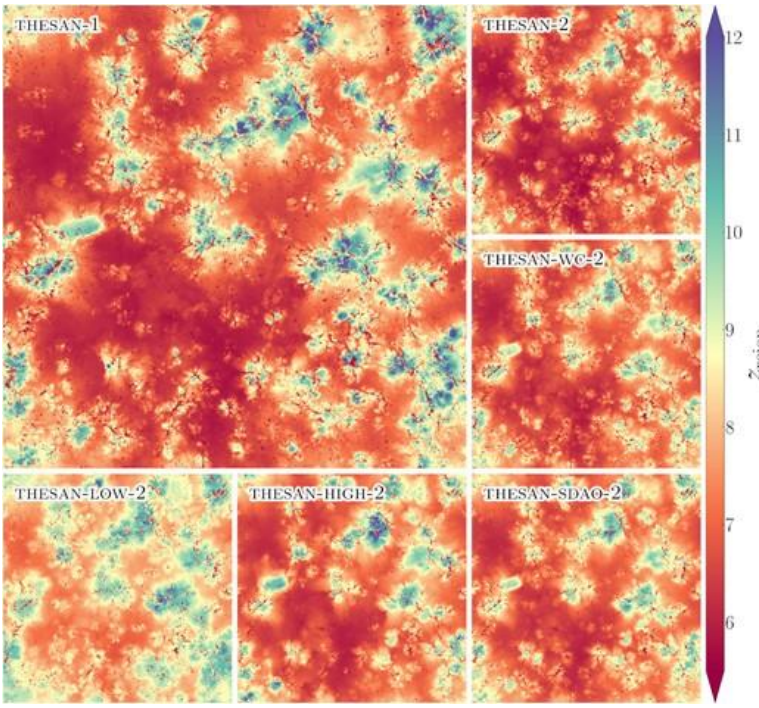

Fig. 2 Visualization of re-ionization redshift which is the z value when the hii value over exceeds 0.99, or fully re-ionizes.

One of the other results obtained in the THESAN simulation is about the Lyman-alpha emission in the period of re-ionization. Through graphing the evolution of transmitted flux the THESAN research team have found many useful information about the Lyman-alpha emission. In the research the team found that same line of sight extracted from the THESAN-1 run. As expected, the number of transmission regions grows with redshift [13]. The research team also compares the transmitted flux values obtained from the simulation with values computed from observed high-z quasar spectra [12]. In the comparison the team found that both THESAN-1 and THESAN -2 corresponds to the observed data. THESAN-HIGH-2 shows a greater amount of flux due to the great amount of high mass halos who are the major photon emitters. This is also the reason why THESAN-LOW-2 has a different pattern due to its lost of high mass halos meaning a loss of photon ejection source and that the small mass galaxies which are the only source of photons for THESAN-LOW-2 are disappearing at the end of the re-ionization era.

5. Observations

One of the purposes of the THESAN simulation was to correspond simulation results and make predictions that will probably correspond with the observation results, for example as one sees in the previous simulation chapter where the transmission flux that are previously observed matches the results of simulation from the THESAN-1 project. Thus in the following paragraphs it will present several possible ways of observing data corresponding to the re-ionization era. A direct detection of the structure of neutral hydrogen, and how it evolves in time, is possible using the 21 cm hyperfine transition [13]. The 21 cm line is also known as the hydrogen line is a emitted microwave when a spin-flip transition is performed. This line is also a sign for the presence of neutral hydrogen which is important in detecting the ionizing process in the re-ionization era. This line has also a advantage in observing because it can penetrate dust clouds in the cosmos better than the electromagnetic waves. Researchers can even obtain information about galaxy mass and velocity, through analyzing them researchers map out the re-ionization era. But there is a great amount of signal lost and contaminated signals when detected, reemphasizing the importance of analysis pipeline efficacy and signal loss simulations [13].

Another way of exploring the era of re-ionization has been started after the successful launch of the James Webb Space Telescope, which is a ten billion dollar cost space telescope built by a collaboration of different engineers having the strongest detection ability in infrared section of the spectroscope. The successful launch and deployment of JWST has quickly transferred the study of the $z > 5$ universe [14]. This great ability of detection leads people to be able to see images or signals from high redshift galaxies where information about the era of re-ionization comes from. The birth of this space telescope lead the obervational limits from $z = 8$ to around $z = 20$ leading in a great amount of information that can be used to observe the re-ionization era. Moreover, it can detect more accurate stellar masses, detailed galaxy structures, and other emission lines. Using these observed data with the data from the THESAN simulation can help test the reliability of the THESAN simulation data and also a contrast using the observed data and the simulated ones' with different models can more detail show the strength and weakness of the model.

6. Limitations and Prospects

The THESAN simulation has been a very successful simulation project that reveals the history of the re-ionization era and tells scientists what happened in the era. Its results have also been proved by the observational studies performed by the James Webb Space Telescope there are still certain limitations in this area and some furture outlooks that will discussed further on in this passage. One of the greatest limitations in this field is still the problem of power of calculation the computer can have. Having models like the THESAN model which are advanced and have been prove useful (previous IllutrisTNG model) is not the only factor required in computer simulation studies for cosmology. The ability of calculation is one factor that greatly influences this field. The models can be very more accurate than it is now, however it would take up too much arithmetic power that can not be performed. Giving up resolution to make simulations able to be performed has a effect on the accuracy of the final solution. It is not that the images or data that researchers will get is blur but because some small reactions may occur that will effect the entire picture greatly afterwards will not be calculated. For example, The observational uncertainties in the UVLF beyond MUV ∼−15 are well represented in the simulations with the medium resolution runs showing a turnover at around the same magnitude as determined by Atek et al. [15]. This is not present in THESAN-1 due to its superior resolution and is in better agreement with observations from Bouwens et al. [16]. In addition, there is another problem that you might need to give up following some factors in order to perform the simulation. For example, the radiation solver in the THESAN project, it limits itself to track the ultraviolet part of radiation. Because of the weakness of the computer causing the two problems that just mentioned, the computer simulation process are limited.

However, despite computer simulations has it limitations, its full potential have not been dug yet. One of the greatest things that computer simulation can continue is by finishing the re-ionization era, because the prediction of re-ionization ending at redshift z = 5.5 was incorrect leading certain dense structures in the universe still neutral, this is one direction of perfecting this program. Second of all, after the launch of the James Webb Space Telescope, there are going to be more and more images and data observed about the re-ionization era and high redshift galaxies. This is like a unexplored treasure, researchers can connect simulations performed by the computer with observations done by the telescope in order to test model’s accuracy and through comparison between models find better solutions. Through these two possible ways, the simulation can reveal more information taking off the secret mask of the re-ionization era.

7. Conclusion

The THESAN simulation is a very great step of human’s understanding of the re-ionization era. It reveals the history of teh change universe. This study summarized the part of the or most of the THESAN project. The THESAN project is a cosmological simulation in order to reveal the history of the re-ionization era, which is when the universe is ionized again by high energy particles emitted by galaxies. In the THESAN simulation model there are majorly three parts, the radiation algorithm, a advanced model of the previous IllustrisTNG galaxy formation model, and the cosmic dust model. Different simulations have been performed each with different models or conditions. Using these conditions the team tracked down the ionizing history where galaxies form then it starts ionizing in places close to the galaxies and then further away. It also predicts transmission flux that is the same as the observed ones. However there are limitations on this program due to calculation powers, but there is still things to be found through combining data from JWST. This study summarizes the gigantic system built on the THESAN project so that people can have a better understanding of the THESAN project.

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