# Analysis of the Lyman-Alpha Forest and Reionization Based on THESAN

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**Abstract.** As a matter of fact, the universe is composed of 70% invisible dark matter, and approximately 20% of dark energy. On this basis, it is crucial to consider how one can observe those compositions with our naked-eyes. In terms of prediction of the universe's earliest birthing throes, the astrophysics simulation gives us a glimpse into prediction, which in turn makes valid comparison between simulated project and real-world situations. THESAN is currently the most advanced reionization simulation in the field. For high redshift universe, z=6, the reionization model reveals the intergalactic medium (IGM) is highly radioactive. We further compared the different models of equations governing the evolution of radiation through IGMs. The Lyman alpha forest visualizes the reionization evolution, hydrogen distribution, and other information of early universe. By using mathematical deduction and Python simulation, the mechanisms of the THESAN simulation are explained. Overall, these results shed light on guiding further exploration of reionization process.

**Keywords:** THESAN; Reionization; Lyman-Alpha Forest.

## 1. Introduction

Since the big bang, the universe has been constantly evolving. It has gone through several different phases. For example, the reionization period is when gas particles lost their electrons as a result of the UV radiation from newborn stars; the ionized hydrogen density increased significantly in the Epoch of Reionization [1]. The history of the universe reveals much about the mechanisms of the current universe. Astrophysics, a special branch of physics, cannot use experiments to support a hypothesis or theory. A great alternative to experiments is to simulate the universe computationally and compare the theory with astronomical observations. The reionization period is an especially interesting stage for the universe, which is what the leading simulation THESAN focuses on. Modeling different stages or physic models of the universe can provide great insight to the existing physics knowledge: dark matter only or baryonic matter only universe [1]. Early simulations in astrophysics relied on analytical models, limiting their ability to capture the complexity of astrophysical phenomena. However, the advent of numerical techniques marked a turning point. One significant milestone was the pioneering work of the physicist Subrahmanyan Chandrasekhar, who developed the first numerical model to understand the behavior of stars [2].

As computing power increased, astrophysical simulation programs started utilizing more realistic and detailed models. The utilization of parallel processing, spreading computational tasks across multiple processors, enabled faster and more accurate simulations. This breakthrough allowed for the exploration of dynamic processes in astrophysics, such as galaxy formation and stellar evolution [3]. Astrophysical simulations have progressively incorporated various physical processes to enhance accuracy and realism. The inclusion of hydrodynamics, radiative transfer, and magnetohydrodynamics (MHD) expanded the capabilities of simulation programs. This integration has proven crucial in studying phenomena like accretion disks and star formation. The advancement of astrophysical simulation programs aligned with the era of big data and observational astronomy. To bridge the gap between simulations and observations, data assimilation methods were developed. These techniques enable the integration of observational data into simulations, refining the models and providing critical insights into astrophysical processes.

The latest frontier in astrophysical simulation programs lies in the integration of machine learning and artificial intelligence (AI). These techniques allow for the acceleration of simulations, optimization of parameters, and identification of patterns within vast datasets. The convergence of AI and astrophysics holds great promise for solving complex astrophysical puzzles and analyzing extensive datasets obtained from telescopes and space missions [4]. Lyman-alpha Forest is widely accepted as a tool for studying the early universe history. What the Lyman-alpha Forest reflects includes reionization history, hydrogen distribution history, and other factors that might impact the absorption lines in the spectrum. This paper seeks to conclude the former development of Lyman-alpha forests that researchers made in the last decade, aiming to present a relatively comprehensive picture of the Lyman-alpha Forest. Besides interpreting the results that scientists gained, this paper also presents some innovative ideas and simulation to present a further and deeper insight into the Lyman-alpha forests. This paper will offer the THESAN projects description, reionization epoch, and Lyman alpha forest's basic theory, concluding frame of the Lyman-alpha Forest. This paper will also conclude and create the simulation results. To be comprehensive, this paper issues some limitations of the Lyman alpha forest, pointing out the potential problem that might exist in future research.

## 2. Basic Descriptions of THESAN

### 2.1. Scientific Goals and Form of the THESAN Project

The scientific goal of THESAN project is to create connection between galaxies and medium. It focuses its attention on the first billion years after the Big Bang. After the Big Bang, the universe undergone a very special period, during which the stars and galaxies emitted enormous amounts of Lyman continuum radiation. This specific period is also called the Epoch of Reionization (EoR) There are many questions unknown about the Reionization period, such as what are the properties of the sources that cause the reionization, the duration of the process, and what is the temperature range of the intergalactic medium. Because of the high redshift and low IGM density, it's hard to gain a comprehensive and accurate insight into the EoR. In the THESAN project, scientist designed a innovative simulation to leverage high redshift observations to constrain the physics of reionization. Also, they aim to investigate how did Lyman continuum radiation escape influence the induced reionization, various dark matter models, and convergence in numerical way [5].

The form of the THESAN project is large volume radiation hydrodynamic simulations, and it combines many other astrophysics equipment and methods to make its own predictions and simulations, such as the Illustris model and James Webb Space Telescope. Given the content of the universe (dark matter, dark energy, particles, magnetic fields, cosmic dust) and the initial conditions (density field after the Big Bang), scientists are capable of giving graphs and simulations about the realistic universe, such as the density, temperature, ionization state, and black holes. THESAN simulates the intricate interplay between radiation, gas dynamics, and galaxy formation during the epoch of reionization by combining a number of cutting-edge computational approaches and models. The simulations specifically capture the physical mechanisms that drive the reionization process and determine the large-scale structure of the early universe by combining radiation-magnetohydrodynamics (RMHD) and galaxy formation models. By accounting for the effects of ionization, heating, and cooling on the distribution of the gas as well as the propagation of ionizing photons through the intergalactic medium, the RMHD numerical technique simulates the interplay between radiation and gas dynamics. As a result, the models can accurately depict the intricate feedback mechanisms that drive the reionization process, such as how early galaxies ionize neutral hydrogen and how ionizing radiation then heats and ionizes the intergalactic medium. The creation, evolution, and effects of galaxies on the intergalactic medium are all included in the THESAN project's galaxy formation models. The impacts of star formation, feedback from supernovae and black holes, and the expansion of supermassive black holes at the centers of galaxies are all taken into consideration by these models. The simulations may depict the intricate interactions between galaxies and the intergalactic medium as well as the effects of galaxy formation on the reionization

process by including these physical processes. The THESAN project uses a number of additional cutting-edge methods and models in addition to these foundational ones to increase the precision and realism of the simulations. These include subgrid models for unresolved physics, which take into account the impacts of small-scale processes that the simulations are unable to directly resolve, and adaptive mesh refinement, which enables the simulations to reach high spatial resolution in regions of interest [6].

### 2.2. Methods

During the simulation process, scientists use AREPO-RT to solve the hydrodynamical equations, including the quasi-Lagrangian solution, the second order Runge-Kutta time integration, the least-square fit gradient, and so on. The hydrodynamics equation is a set of partial differential equations that describe the conservation of mass, momentum, and energy in a fluid. The equations are typically written in terms of the fluid density, velocity, and pressure, and describe how these quantities change over time due to various physical processes, such as advection, diffusion, and external forces [5]. The general form of the hydrodynamics equation is:

$$\partial\rho/\partial t + \nabla \cdot (\rho v) = 0 \tag{1}$$

where ρ is the fluid density, v is the fluid velocity, and ∇ is the gradient operator. This equation is known as the continuity equation, and it describes the conservation of mass in the fluid [1]. The Momentum equation is given by:

$$\rho(\partial v/\partial t + v \cdot \nabla v) = -\nabla p + \rho f \tag{2}$$

where p is the fluid pressure, f is any external forces acting on the fluid, and the dot (·) represents the dot product. This equation describes the conservation of momentum in the fluid [1]. Finally, the energy equation is given by:

$$\partial E/\partial t + \nabla \cdot [(E + p)v] = \rho v \cdot f \tag{3}$$

where E is the total energy density of the fluid, including both kinetic and internal energy. This equation describes the conservation of energy in the fluid. These equations are typically solved numerically using a variety of techniques, such as finite difference, finite volume, or finite element methods. In the THESAN simulations, the hydrodynamics equation is solved using the moving mesh method, which is implemented in the AREPO code [1].

There are multiple benefits of using AREPO-RT: one of AREPO's character is the semi-Lagrangian character, which enables the AREPO to simulate large dynamical range systems. Scientists also discussed different force conditions while solving gravity. Long range forces are calculated using the particle mesh method, while short range forces are computed through hierarchical oct-tree algorithm. In order to prevent the correlated force errors, errors that cause by approximately static particle distributions at high redshift simulations, scientist randomize the particles' locations regarding the new calculated domain decomposition. By using the radiation hydrodynamics solver, scientists can therefore understand how light, and gas interact in space, helping to see how light from stars and galaxies can make heated gas in space. The THESAN project is a suite of simulations that model the epoch of reionization in the early universe [1]. While the THESAN project does not directly focus on dust creation and destruction, it does include a semi-empirical model to estimate the dust masses in galaxies [6]. The shock-driven destruction timescale, $\tau_s h$, is given by:

$$\tau_{sh} = \rho_{gas}/(n_{sh} v_{sh}) \tag{4}$$

where $\rho_g$ is the gas density, $n_{sh}$ is the number density of shock waves, and $v_{sh}$ is the velocity of the shock waves. This timescale represents the time it takes for a shock wave to destroy a given amount of dust. The sputtering-driven destruction timescale, $\tau_{sp}$, is given by:

$$\tau_{sp} = M_d/\left(3 n_H \Sigma_{sp} v_{rel}\right) \tag{5}$$

where $M_d$ is the mass of the dust, $n_H$ is the number density of hydrogen atoms, $\Sigma_{sp}$ is the sputtering cross-section, and $v_r$ is the relative velocity between the dust and the gas. This timescale represents the time it takes for sputtering to destroy a given amount of dust. Combining these two timescales, one can derive the equation for the local instantaneous dust destruction rate:

$$dM_{dust}/dt = -M_{dust}/\tau_{sh} - M_{dust}/\tau_{sp}/3 \quad (6)$$

where the negative sign indicates that the dust mass is decreasing over time due to destruction processes, and this is how we can deduce the equation of dust destruction rate, which is the similar process that we use in computing the dust creation rate.

However, the dust-to-mass and dust-to-metal ratios in the THESAN simulations are lower than what is expected, which leads to dust attenuation in luminous halos being not strong enough to match the observational estimates. Therefore, the THESAN project is relevant to the study of dust creation and destruction in the sense that it provides a framework for studying the evolution of galaxies and the interstellar medium over cosmic time. The previous Illustris model explains that the initial conditions are generated using a method in which the initial Fourier mode amplitudes are fixed to the ensemble average power spectrum [7]. This method is used to suppress variance in the initial conditions and ensure that the simulations are consistent with observations of the large-scale structure of the universe. The Illustris project describes how the initial conditions are set up to include the effects of dark matter, baryonic matter, and radiation. The initial conditions are generated at a high redshift, which corresponds to a time when the universe was only 50,000 years old. The universe was still in a state of thermal equilibrium, and the initial conditions are set up to reflect this. Scholars came to the conclusion that their simulations give a complete picture of the reionization process, from the precise characteristics of the galaxies that cause it to the large-scale statistical properties of the intergalactic medium. They explore the relevance of their findings for upcoming observational studies of reionization as well as the significance of integrating radiative transfer effects and magnetic fields in reionization simulations. The identification of a population of faint, highly ionizing galaxies that may have been crucial in reionization, the detection of large-scale anisotropies in the ionization field that may be connected to the large-scale structure of the universe, and the forecast of observable reionization signatures in the 21-cm line of neutral hydrogen are some of the specific conclusions mentioned in the section [1].

## 3. Epoch of Reionization

Reionization refers to the process of ionizing the neutral formed in the early universe. In the very early stage of the universe, the temperature of the universe is too hot for those neutral to even exist. However, about 4 hundred thousand years after the big bang, as the universe cooled down and less dense, the atoms began to form, and most of them are hydrogen and helium [8]. Before the occurrence of the reionization, there was a dark age period, appearing 380 thousand years after the origin of the universe. The dark ages, dominating the universe for a few hundred years, made the whole universe full of neutral hydrogen that was not ionized because of the appearance of the quasars and the galaxies. As a result, most of the light is forbidden from being seen until the reionization, making the whole universe extremely dim and dark [9]. Reionization happened after about 400000000 years later. When emission of the radiation followed by the formation of the early galaxies occurred. Most of the IGM which was neutral was ionized by ultraviolet light that was emitted by the new quasars and galaxies [8], expanding as the process repeating. And eventually, when most of the IGM were ionized, the reionization was considered finished. It's commonly believed that the reionization ended at z=6 [8].

### 3.1. The Basic Equation

Ionizing the hydrogen in IGM, the photons' rate of ionizing those hydrogen have to follow the equation [8]:

$$\Gamma_{\mathrm{HI}} = 4\pi \int_{\nu_{\mathrm{HI}}}^{\infty} \frac{J_\nu}{h\nu} \sigma_{\mathrm{HI}}(\nu) d\nu \tag{7}$$

Here, σ(ν) stands for the cross-section, which means the probability of ionization per unit incident photon energy. Jν simply represents the average intensity [8]:

$$J_\nu(t, \mathbf{x}) = \frac{1}{4\pi} \int d\Omega I_\nu(t, \mathbf{x}, \mathbf{n}) \tag{8}$$

Jν can be interpreted as the equations above. Iν represents the radiation field intensity determined by the time, position, and direction. The electrons which are wandering around the protons will be absorbed in the velocity which is determined by the gas temperature in 10 thousand K. This equation can roughly calculate the result. This equation can contribute to the simulation of the reionization:

$$\alpha_{\mathrm{HII}}^{A}(T) \simeq 4.2 \times 10^{-13} T_4^{-0.7} \mathrm{cm}^3 \mathrm{s}^{-1} \tag{9}$$

### 3.2. The Relationship Between the Reionization and the Lyman-Alpha Forest

Both the IGM and the ionization of the hydrogen and the helium can contribute to the formation of the Lyman alpha forests, influencing the result of the spectrum. Without the impact of the reionization, the Lyman alpha forests rely on hydrogen clouds. However, with the existence of the ionization, the Lyman alpha forests can be less susceptible to the absorption line because a lot of IGM became ionized again [10]. So, the epoch of reionization can be interpreted by the Lyman alpha forest because of the influence that the reionization caused on the Lyman alpha forest. The graph of the Lyman alpha forests can simply reflect the epoch of the reionization by deeply observing the subtle differences shown in the graph. This study includes the transition between the neutral dominated epoch to the reionization epoch, which are all amazingly shown in the Lyman alpha forests. The Lyman alpha forests can study the whole history of the IGM in a similar way [10]. What's needed to be pointed out is that the redshift can exert the difference in the simulation.

## 4. Lyman-alpha Forest

Lyman alpha forest is from hydrogen absorption. The simulation which has been repeated thousands of times showed that Lyman alpha forest can result in indication that gravitation is unstable in universe dominated by the cold dark matter and energy. The Lyman-alpha Forest seeks to observe in the cosmology term to articulate the numerous absorption lines which can attribute to the intervening neutral hydrogen's ability to alter the spectra originated from the quasars that's far away from the medium composed by the neutral hydrogen, creating distinct forest-like spectrum [11]. For instance, the Fig. 1 shows the relationship between the projected gas density and the component in a set velocity [12]. When photons that reach the IGM approach with the neutral hydrogen, the energy transition will happen in the process of matching the wavelength of the Lyman alpha forest wavelength, which is widely accepted that the wavelength is 121.6nm, causing the absorption of the photons. Simplified by summarizing it, the Lyman-alpha Forest is a term that allows people to see the absorption line on the quasar spectrum that's far away from us, which is formed under the influences of neutral hydrogen [13].

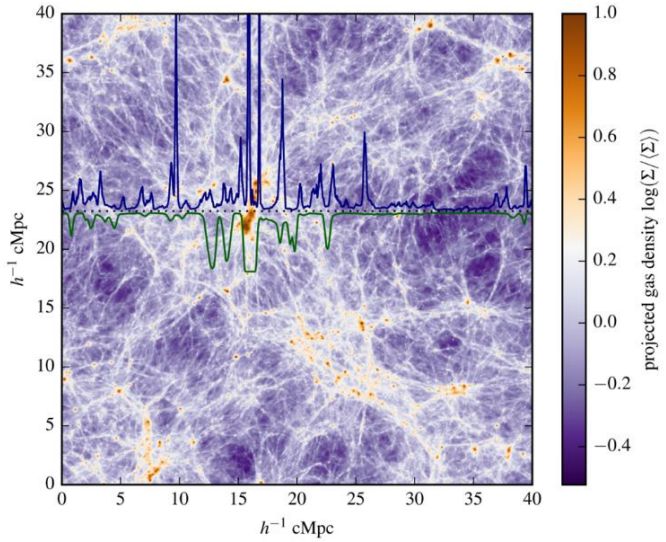



**Fig. 1** Relationship between the projected gas density and the component in a set velocity.

The goal of learning about the Lyman alpha forest is to get deeper insight into the IGM evolution history. By carefully examine the Lyman alpha forest, observing the distribution lines, density, and other factors can lead to different conclusions of certain period of the history. Both the thermal and ionizing history can be indicated from the Lyman-alpha Forest [11]. There are a few fields applying the Lyman alpha forests. The Lyman alpha forests can offer an observation history of the intergalactic medium in the comic time scale. Redshift and other factors that can be indicated by the Lyman alpha forest spectrum can contribute to the study of the thermal and ionization history of intergalactic medium [12]. Besides, Lyman alpha forest can also be used as a toll to constrain the cosmological parameters. By saying constraining, the researchers mean matching the data with the simulation and the models is a relatively easy way to examine the concealed cosmological parameters. In a less broad term, the galaxy formation and evolution can also be carefully studied by the according to the potential influences that galaxies might have exerted on the surrounding intergalactic material [12]. Analyzing the spectrum in different redshifts, researchers will indicate some functions like luminosity's, which is highly valuable and worth learning.

## 5. Simulation Results

This section will explain the THESAN simulation of radiative transport equations and the simulation of this research. Radiative transport equations describe the propagation of radiation through space, affected by absorption and emission of intergalactic field in between the observer and the source. THESAN radiative transfer equation:

$$\begin{aligned} \frac{\partial E_{\mathrm{r}}}{\partial t} + \nabla \cdot \boldsymbol{F}_{\mathrm{r}} &= S - \kappa_{\mathrm{E}} \rho \tilde{c} E_{\mathrm{r}} \\ \frac{\partial \boldsymbol{F}_{\mathrm{r}}}{\partial t} + \tilde{c}^2 \nabla \cdot \mathbb{P}_{\mathrm{r}} &= -\kappa_{\mathrm{F}} \rho \tilde{c} \boldsymbol{F}_{\mathrm{r}} \end{aligned} \tag{10}$$

The equation is the system of partial differential equations is the radiative transfer equation, which describes the change of the energy density and radiative flux with respect to time. On the left-hand side of the first equations, the partial derivative of energy density is added to the second term, which refers to the divergence of radiative flow in space [13]. On the right-hand side, the interference factors are shown. S represents the external radiation source, accounting for the emission of the intergalactic medium; κE describes the energy density-weighted mean opacities of the medium in a specific frequency range, which accounts for the absorption of the medium [13]. Lastly, ρ and c~ represent the gas density and signal speed respectively. The second equation shows the partial derivative of radiative flux and the divergence of the radiation pressure tensor. KF refers to the flux-weighted mean opacities:

$$\begin{aligned} \frac{\partial E_{\mathrm{r}}}{\partial t} + \nabla \cdot \boldsymbol{F}_{\mathrm{r}} &= 0 \\ \frac{\partial \boldsymbol{F}_{\mathrm{r}}}{\partial t} + \tilde{c}^2 \nabla \cdot \mathbb{P}_{\mathrm{r}} &= 0 \end{aligned} \tag{11}$$

In the THESAN simulation, the free transport radiation is used. All the emission and absorption by the intergalactic medium are ignored. The right-hand side is set to zero:

$$\frac{\partial \mathcal{U}}{\partial t} + \nabla \cdot \mathcal{F}(\mathcal{U}) = 0 \tag{12}$$

where

$$\mathcal{U} = \begin{pmatrix} E_{\mathrm{r}} \\ \boldsymbol{F}_{\mathrm{r}} \end{pmatrix}, \mathcal{F}(\mathcal{U}) = \begin{pmatrix} \boldsymbol{F}_{\mathrm{r}} \\ \tilde{c}^2 \mathbb{P}_{\mathrm{r}} \end{pmatrix} \tag{13}$$

To solve this, this system of hyperbolic partial differential equation is written as a compact conservative form shown above. AREPO-RT uses a finite volume method to solve the conservation equations. It discretizes the computational domain into a finite number of cells using Voronoi Tessellation. The conserved quantity, vectors of energy density and flux density shown above, is cell averaged within the volume to get the approximation. Integration and numerical approximation are used:

$$\mathcal{Q} = \int_V \mathcal{U} \mathrm{d}V \tag{14}$$

Gauss' theorem can be used then to gain an approximation of the change of conserved quantity with time. In the THESAN simulation, AREPO-RT uses a quasi-Lagrangian framework to track radiation. In a full Eulerian framework, the mesh cells are static. The $\omega$, representing the velocity of the mesh cells, is zero in that case. In a full Lagrangian Framework, the mesh cell boundary moves with the velocity of the fluid. $\omega$ is equal to the local velocity of the gas. In AREPO-RT, $\omega \neq 0$ and $\omega \neq$ v. It does not move according to the local flow velocity. Instead, the velocity is somewhere in between as it is hard to track the gas exactly in multidimensional flow.

$$\frac{\partial \mathcal{Q}}{\partial t} = -\int_{\partial V} [\mathcal{F}(\mathcal{U}) - \mathcal{U} w^T] \mathrm{d}A \tag{15}$$

The − U $\omega$ T represents the advection step, which tracks the movement of the cell mesh while F(U) is just the static flux value. For regular hydrodynamics and MHD, AREPO ensures Galilean invariance, which means that the same law of fluid dynamics remain consistent regardless of the reference frame. However, since photons have a different property in relativity, they do not have Galilean invariance. Riemann solution, Godunov's method, and the unsplit approach are used to ensure mesh frames are included and accuracy is improved [11]. The Reimann problem describes when there are discontinuities in solutions. For example, shock waves might propagate in between interfaces of the mesh cells. The Godunov's approach can describe fluid properties near the discontinuity [13]. Unsplit method then solves the equation holistically since the domain is unstructured. Lastly, the Riemann solution is fed into the Harten-Lax-van Leer (HLL) framework to gain the actual numerical solution and smooth the intercell fluxes for numerical stability [12].

The simulation of this research tracks the gas movement from a different perspective. The radiative transport equation focuses on the intensity of the gas of a specific frequency range.

$$\frac{dI_v}{d\tau_v} = S_v - I_v \tag{16}$$

The change of the intensity of a gas with respect to the optical depth is related to the emission of the source term and the absorption of medium. Actually

$$d\tau_v = \alpha_v ds \tag{17}$$

The optical depth is a unitless term that purely describes the intensity depletion. Adding it to the equation leads to the final form of the equation. We have the formal solution to the problem.

$$I_v(\tau_v) = I_v(0)e^{-\tau_v} + \int_0^{\tau_v} S_v(\tau_v')e^{(\tau_v'-\tau_v)}d\tau_v' \quad (18)$$

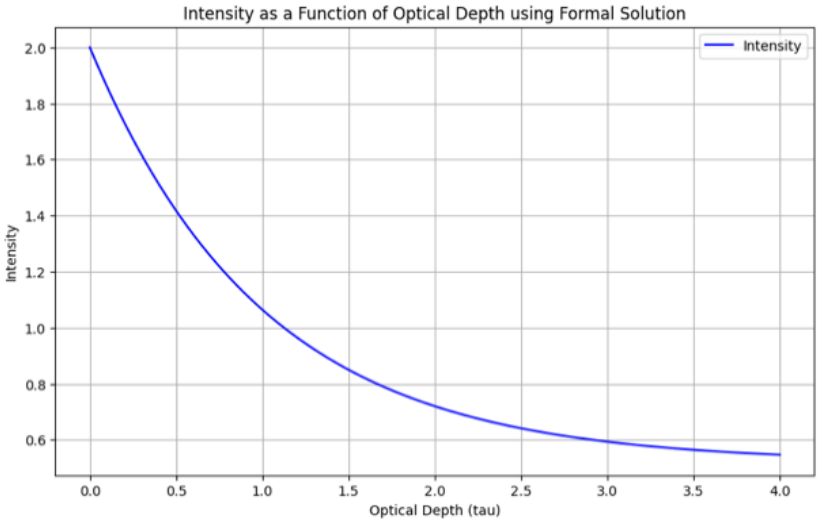



**Fig. 2** Intensity as a function of optical depth.

Although equations from both simulations focus on radiative transfer equations, the perspective is different as THESAN focuses on the energy density and flux of the radiation while the simulation of the research focuses on the intensity. One focuses on the concentration while the other focuses on the flow of the wave. THESAN has a more comprehensive equation accounting for the various factors. It can be applied in non-equilibrium conditions and includes spatial variation. However, it can be quite computationally expensive as it is run on supercomputers. The second equation is direct and simple to simulate but do have a limited scope; it often assumes local thermodynamic equilibrium. It focuses on the spatial evolution instead of the temporal evolution, which can be beneficial. The result of the simulation is shown below in the graph. The mid-range temperature of all the stars were used to determine the temperature of the medium in the simulation. The emissivity coefficient was set to 0.5. The simulation was compared when source function $Sv$ is a Planck blackbody function and when the medium is not in thermodynamic equilibrium. The speed of depletion is higher when it is not in thermodynamic equilibrium. As intuitive as it is, increased optical depth meant more fractional depletion by the nature of the definition. The results are given in Fig. 2.

## 6. Limitation & Future Outlook

Although the THESAN project has already made a huge step in assisting us to better simulate the early state of our universe, there are still many limitations and drawbacks that we should consider and make improvements. For example, the simulations assume a simplified model of star formation and feedback, and do not include the effects of feedback from black holes or other sources of radiation. For example, black holes are thought to play an important role in regulating star formation and the growth of galaxies, and their feedback can affect the properties of the intergalactic medium and the ionizing photon budget. Similarly, other sources of radiation, such as X-ray binaries or Population III stars, could also contribute to the ionizing photon budget and affect the reionization process. By neglecting these effects, the THESAN simulations may be underestimating the complexity of the reionization process and the role of different sources of radiation. Additionally, the simulations are limited by the available computational resources and the current state of our understanding of the relevant physical processes. Finally, the simulations make several simplifying assumptions about the initial conditions and the properties of the intergalactic medium, which may affect the accuracy of the results. For instance, the simulations assume a homogeneous and isotropic universe, neglecting the effects of large-scale structure and cosmic variance. Additionally, the simulations assume a uniform and static UV background, neglecting the effects of fluctuations and temporal variations in the ionizing radiation field. Finally, the simulations assume a simplified model of the intergalactic

medium, neglecting the effects of magnetic fields, turbulence, and other physical processes that may affect the reionization process.

In future further study, firstly, we hope to dig deeper into higher redshift conditions, and to take the multi-physical field effects and dark hole into account. Secondly, another important aspect is to validate the simulations of the THESAN project against realistic observational data, to ensure that they accurately reproduce the statistical and spatial properties of the intergalactic medium and the galaxies that drive reionization. This can involve comparing the simulations to observations of the cosmic microwave background, the Lyman-alpha Forest, and other probes of the early universe, and using statistical techniques to constrain the properties of the intergalactic medium and the sources of ionizing radiation. Finally, the THESAN project can gain improvements from interdisciplinary collaborations with fields of computer science, data analysis, and visualization, to develop new tools and techniques for analysing and interpreting the large volumes of data generated by the simulations [1]. By pursuing these avenues of research, we hope that the THESAN project can continue to push the boundaries of our understanding of the early universe and its evolution, and we wish to continue to investigate new discoveries and breakthroughs in astrophysics and cosmology.

## 7. Conclusion

The THESAN project combines mathematical equations and previous observational equipment to predict the conditions of high redshift galaxies, such as the initial conditions, the dust creation and destruction rate, and so on. The Lyman-alpha Forest can gain us further insight into the epoch of the reionization, observing the history of the reionization epoch. By studying both the equation of the reionization rate and the Lyman-alpha Forest, researchers can simulate the spectrum at different redshift levels. The basic form of the Lyman alpha forest responds to the absorption line of the neutral hydrogen, forming dark lines. By learning spectrums of the Lyman-alpha Forest, the distribution of hydrogen in the early universe, reionization epoch can be all learned. The radiative transfer equations describe the movement of radiation through space. In THESAN and the simulation of this research, two different equations with different perspectives were compared to understand the advantage and disadvantage of each method. Although the THESAN project has made a significant progress and laid a solid foundation for the prediction of astrophysics world, we still have to consider about the influenced brought by multiple physics field and dark holes. This paper provides a detailed overview of the complex equations used in THESAN and a specific comparison with our own simulation in the part of radiative transfer equations.

## Author Contribution

All the authors contributed equally, and their names were listed in alphabetical order.

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