Analysis of Line Intensity Mapping, Dust Grain Radiation, Lyman-α Emission and Transmission

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Abstract. Existing models of the universe consider the combined effects of neutrons and dark matter. While the properties of neutrons are well understood, depicting galaxy formation and understanding the universe through spectral images remains a major research direction. This study can be classified into two disciplines: Cosmology and Astrophysics. Astrophysicists focus on the evolution of galaxies, while cosmology studies the universe on a larger scale, including interactions of dark matter and dark energy. Cosmologists mainly obtain data through cosmological simulations, which play an important role in cosmology research. However, existing computers struggle with the complex calculations involved. One possible solution is simulating cosmic fluid dynamics, which can effectively simulate large volumes but cannot simulate detailed information. The THESAN project has achieved important research results but also has some defects. Existing articles have summarized THESAN's characteristics and shortcomings by comparing its expected simulations with observational data. This paper summarizes the existing problems and introduces solutions, focusing on THESAN's improved simulation method for the Lyman-alpha emission spectrum and its simulation of cosmic dust. We talk about 3 new techniques used in the simulation of THESAN.

Keywords: Reionization, dust grain radiation, Lyman alpha emissions, THESAN Project.

1. Introduction

Existing models of the universe consider the combined effects of neutrons and dark matter on the universe. Although the physical properties of neutrons are easily explained, how to depict the formation of galaxies and understand the universe through images of spectra remains a major research direction. The main research can be classified into two disciplines: Cosmology and Astrophysics [1-3]. Astrophysicists are focusing on the evolution of galaxies. Cosmology mainly studies the considers the universe on a larger scale including interactions of dark matters and dark energy. Indeed, in addition to observing live data through various telescopes, cosmologists mainly obtain data through cosmological simulations. So cosmological simulation plays an important role in cosmology research. Cosmological simulation operates the universe by considering dark matter, dark energy, and neutrons, and their relevant evolutionary equations. But existing computers cannot handle such complex calculations. However, the simulation of cosmic fluid dynamics is one possible solution. This simulation baryons start from ΛCDM initial conditions and follow the coupled dynamics of dark matter. This method cannot simulate the formation of information and important details of ISM, but it is very effective for simulating large volumes. Typically have a mass resolution of about ~10^6M⊙.

The THESAN project has achieved many important research results since its inception, but the THESAN project also has some defects. Many existing articles have summarized THESAN's characteristics and shortcomings in specific areas of observation by comparing THESAN's expected cosmological simulations with observational data. These problems have common characteristics, and there are ways to focus on improving the problem. In this paper, the existing problems are summarized and summarized, and the solutions are briefly introduced. In this paper, we mainly introduce THESAN's improved simulation method for the Lyman-a emission spectrum, which solves the atomic cooling halo of the entire universe (95.5 CMpC)3 region. At the same time, the large volume and high-resolution THESAN simulation is summarized to simulate the 21cm spectral emission lines

of ISM and hydrogen atoms in the universe, and the fitting accuracy of the main emission spectral lines to L-SFR under different redshifts is analyzed. At the same time, it summarizes THESAN's simulation of cosmic dust: Dust is directly treated using live simulation particles, each of which represents a population of grains that are coupled to hydrodynamic motion through a drag force.

2. Basic Theory

With the use of a brand-new simulation called THESAN that was created by researchers in Astrophysics, scientists may now gain a thorough understanding of how the universe may have grown at this critical time. THESAN, which takes its name from the myth, aims to replicate the " dawn," more precisely cosmic reionization. This epoch has proven difficult to reproduce because it includes incredibly complex, chaotic interactions involving gravity, gas, and radiation. THESAN uses three fictional simulations to thoroughly examine the universe's creation, development, and expansion in all of its aspects. Some of the specifics of the three simulations will be described in detail in this paper to offer a deeper understanding of THESAN. They are a self-consistent account of cosmic reionization, a model for cosmic dust, and the advanced galaxy formation model. The Advanced Galaxy Formation Model (AGFM) is a sophisticated computer framework for simulating the complex procedure of galaxy formation and development. The model offers an in-depth understanding of galaxy formation by fusing cutting-edge technology using observational data. The importance of dark matter in the distribution of matter and the process of galaxy formation is shown by this innovative model, that correctly reflects the impacts of dark matter. It also includes systems of feedback, like the effect of stars, black holes, and supernovae on the features of galaxies. One of the most important questions in this rapidly expanding discipline is how to understand the geometry of mass ionization, also known as the geography of heavy ions, or the size and geographical distribution of ions and neutral spots, and how they change over time [4].

It offers a thorough and cogent explanation of the process by which the neutral intergalactic medium turns into an ionized one. This method provides a thorough description of the intricate process of cosmic reionization by taking into account the ionizing radiation released by early galaxies and the consequences of gas density variations. It opens up important new perspectives on the origin and development of our universe by enabling researchers to investigate the genesis and evolution of cosmic structures during this pivotal time. The addition of cosmic dust, the THESAN simulations' final novel component, makes this effort even more distinctive in the field of astrophysical simulations. The term "cosmic dust" refers to a collection of little granules of solid matter that originate in galaxies and are found between stars. One adverse effect of dust is that it confines a portion of the heavy element-derived atomic and molecular gases to amorphous and crystalline forms, which can significantly affect the cooling and chemistry of the cosmos.

Here are a few important scientific fields that are covered by THESAN: Observational operations with the JWST will offer unheard-of samples of Ly emitting galaxies (LAEs), observations of the hyperfine transition of neutral hydrogen, and other observations for studying the IGM through the Lyman-alpha (Ly) forest. Also, In the high-redshift Universe, LIM is quickly becoming a potent method for studying galaxy formation and cosmology [5]. The remainder of the paper will go into further depth about each of these points.

3. Line Intensity Mapping

Fig. 1 presents the UV luminosity functions at a UV wavelength of 1500 Å for red-shifts (z) ranging from 6 to 10 (z=6-10). The solid line represents the luminosity function simulated with dust-related effects, while the dashed line represents the luminosity function simulated intrinsic. The data points represent observational results. From the image, it can be observed that at higher redshifts (z > 7), both the dust corrected and intrinsic simulations match the observational results. However, at z =

6, the simulation results at the high-mass end are slightly lower than the observed results. This discrepancy may be attributed to an underestimation of the (DTM) ratio during the simulation.

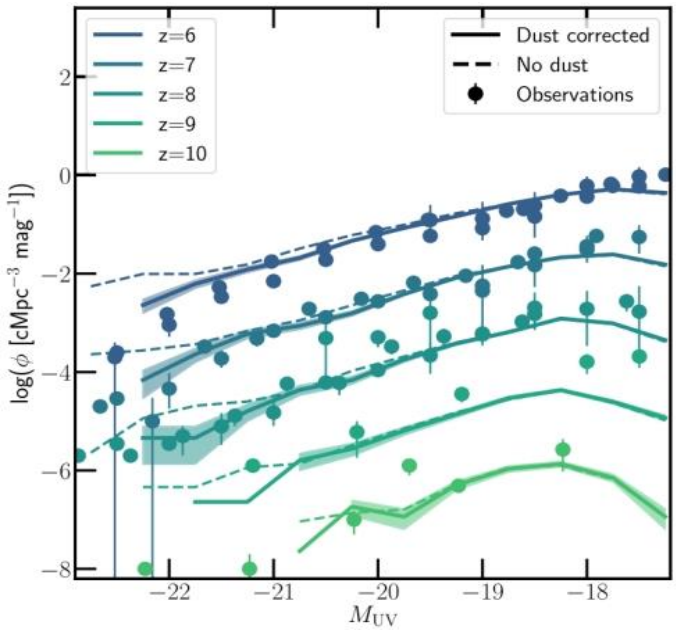


Figure 1. UV spectrum at rest frame 1500À luminosity functions at 2 = 6-10 form THESAN-1

According to previous study, it is observed that under low Red-shift conditions (z = 6-7), the simulation results are similar to the other two simulations [6]. However, under high Red-shift conditions (z = 8-9), the simulation results are slightly lower compared to the other two simulations. The bottom row displays the slope of the ßUV magnitude, which describes the information about the galaxy formation history, about the UV magnitude. It is shown that under the condition of low Muv (UV magnitude) and low Shift, the simulation results do not match the other two results. This discrepancy can be attributed to the fact that most of the simulated galaxies are dust-free, which leads to a deviation when simulating high-mass galaxies.

The THESAN simulation examines the relationship between the brightness of emission spectra of eight different elemental lines and the star formation rate (SFR) at redshifts ranging from 6 to 10 (z=6-10). The black dashed line represents the simulation results, while the dashed lines of other colors represent estimates from other studies. The luminosity functions can be described as a piecewise linear representation, which is evident in OII, OIII, and Hß. paper is styled. The OII and OIII functions show a significant deviation between the simulation results and the estimates from other studies as the SFR increases. The deviation pattern alternates from large to small and then back to large differences. This can be attributed to the underestimated metallicity in the HII regions in the simulation. The NII function exhibits a slope of approximately 1.8, which is much larger than the observed slope of 1. This is because the simulation focuses only on low-redshift galaxies and does not consider sufficient dust attenuation on the luminosity. The CII function displays simulation values much lower than the estimates from other studies. This is due to the complex nature of simulating CII lines, as the simulation does not account for the presence of photo-dissociation regions (PDR) and CO-dark regions. The THESAN-ZOOMs simulations will provide more accurate representations of these aspects [7].

Line intensity maps can be defined as follows:

$$I_v = \frac{c}{4\pi}\frac{1}{vH(z)}\frac{\Sigma L_v(SFR)}{V_{box}} \tag{1}$$

where c is the speed of light, ν is the frequency of the emission line in the rest frame of the galaxy, H(z) is the Hubble constant at Red-shift z, Lν is the luminosity of the emission line, and Vbox is the comoving volume of the simulation box [6]. Fig. 2 shows the variation of the 21cm spectrum at

different redshifts (z=9-6 from left to right). The intensity of the spectrum reflects the density of neutral hydrogen atoms because the 21cm radiation is emitted through the spin-flip transition of neutral hydrogen. From the image, it can be observed that as the redshift decreases, indicating an older age of the universe, the concentration of neutral hydrogen atoms gradually decreases. This indicates the ionization of neutral hydrogen sources during the epoch reionization.

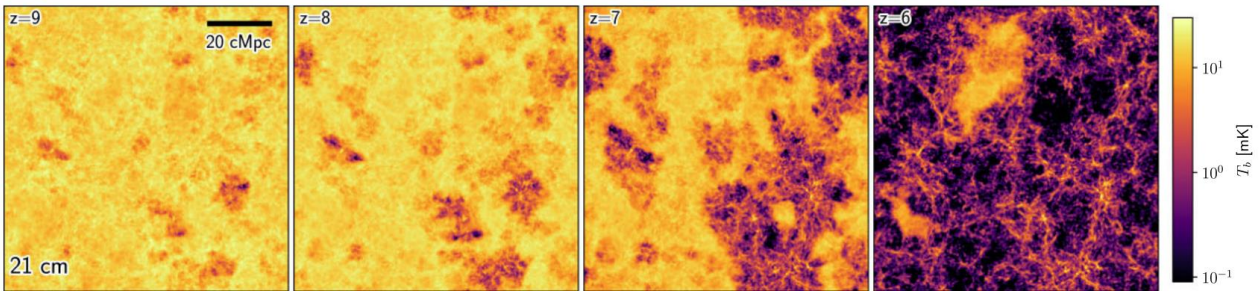


Figure 2. The 21 cm emission maps at z =9-6.

Fig. 3 depicts the spatial distribution of the emission spectra of Hα and OIII. The images correspond to the cases at z=9-6 from left to right. It can be observed that as the redshift increases, the intensity of the emission spectra for hydrogen and oxygen atoms also increases, indicating the ionization of atoms in the universe. Furthermore, comparing the two images reveals a high similarity in the spatial distribution of the emission spectra for oxygen atoms and the intensity distribution of hydrogen atoms. This is because the THESAN hypothesis assumes that all emissions originate from the HII regions along the line of sight and that the metallicity outside galaxies is sufficiently low to neglect their emission spectra.

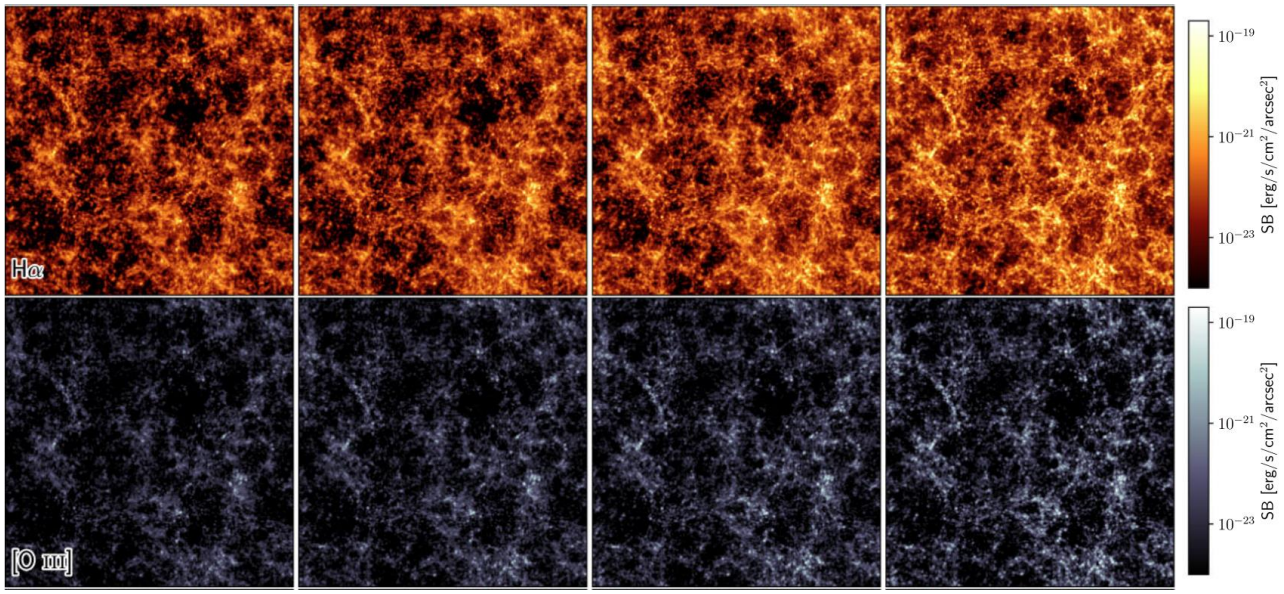


Figure 3. The Hα (at first row) and [OIII] (second row) emission maps produced by THESAN-1 at z = 9-6.

4. Dust Grain Radiation

Before exploring dust grain-radiation coupling, some basic knowledge about cosmic dust is necessary. The term "cosmic dust" refers to a collection of little granules of solid matter that originate in galaxies and are found between stars. Nearly 30 to 50 percent of the light emitted by stars in the Galaxy becomes absorbed by dust particles that exist in the medium that exists between stars. However, nothing is known about dust particles that may exist outside of our galaxy [8]. One adverse effect of dust is that it confines a portion of the heavy element-derived atomic and molecular gases to amorphous and crystalline forms, which can significantly affect the cooling and chemistry of the

cosmos. Along with modifying the way radiation affects galaxy formation processes, dust also converts ultraviolet and optical light into lower-energy photons, sometimes enabling galaxies to shine brightly in the infrared. As a result, dust-reprocessed light has just emerged as a potent technique for examining the characteristics of the first galaxies and is now rapidly disseminating a wealth of knowledge about the early Universe. Additionally, dust grains exert an impact on the strength of magnetic attraction in protoplanetary discs when they are thoroughly mixed with the gas (for example, during the initial stages of accretion or when turbulence precludes them from settling towards the mid-plane) [9]. The integration of cosmic dust, the THESAN simulations' last innovative component, makes this effort even more distinctive in the field of astrophysical simulations. The effective quasi-Lagrangian algorithm AREPO-RT is used in THESAN simulations to track the coupled dynamics of dark matter (DM), gas magnetic fields, and radiation.

THESAN has created a framework known as AREPO-RT that utilizes a moving-mesh algorithm to integrate radiation hydrodynamics with dust physics. Live simulation particles are used to mimic dust particles, while an unstructured mesh is used to manage radiation. THESAN has refined the aerodynamic drag force's implementation to precisely capture dynamics at any dust-to-gas ratio, even ones greater than those observed in the Milky Way. To consistently alter radiation fields, grain characteristics are interpolated onto nearby gas cells in THESAN's methods for simulating the interaction of radiation and dust. The predicted behavior of this approach has been tested by THESAN utilizing a constant brightness source in a medium with initially uniform dust density. The capacity of THESAN to handle multifrequency radiation has been retained while modeling the photon absorption by nearby dust grains. THESAN has shown that a tiny layer of dust with a known optical depth can absorb light. Additionally, THESAN has permitted different temperatures for gas and dust while simulating the energy transfer between the two through impacts. Through infrared thermal dust emission and absorption, dust, and radiation can also interchange energy.

THESAN deviates from conventional radiation hydrodynamics techniques, which estimate dust opacity based on hydrodynamic characteristics using preset values or simplified functions. Instead of making assumptions about local dust-to-gas ratios or distributions, THESAN treats dust as living simulation particles responsive to dynamic pressures, enabling self-consistent computation of dust opacity depending on local grain abundance. THESAN incorporates dust-radiation interaction concurrently with hydrodynamic dynamics, in contrast to previous algorithms that execute radiative transfer in dusty media as post-processing. THESAN offers an alternative to simulations that exclude a direct consideration of dust as radiation hydrodynamics-based computer models of galaxy formation grow increasingly practical [8].

5. Lyman-α Emission and Transmission

Lyman alpha emissions are weak when observing them, and they are largely affected by dust and gas-phase metallicity, which compared to oxygen abundance, is not as significantly correlated to Lyman alpha emission [9]. A measure of the luminosity of a star or galaxy could represent Lyman alpha emission, therefore graphs describing luminosity as a function are significant. However, the distribution functions of stars and galaxies serve as the background knowledge and the exposition of Lyman alpha emission. To begin with, the relative distribution of stars as a function of stellar age increases as stellar age increases but decreases as the stellar age increases when it passes a certain value x. For a mass-centered system, x is 160 Myr, which is also the median age, at a redshirt of z=6. For a Lyman alpha emission system, x is 3Myr, at a redshirt of z=6, which is also the median age. On the other hand, the cumulative distribution function increases for both mass and emission-centered systems.

Secondly, as the galaxy halo and stellar mass increase, the density of galaxies decreases over the range of redshifts of 6 to 10. The higher the redshift is, the faster at which its density decreases. On the other hand, the smaller the redshift, the larger the density of galaxies at a given mass, both stellar and halo [10]. Now, luminosity as a function of stellar and halo mass. According to the analysis, it is

suggested that there are more galaxies with a comparatively small stellar mass and a relatively small luminosity. Beisdes, stellar luminosity plays a prominent role when the halo mass of a galaxy is around 8 times the mass of the sun and the overall luminosity is around 41 units. The stellar luminosity will be almost 0 if the overall luminosity is around 38 units for the same halo mass. In addition, intergalactic medium transmission increases as velocity offset and rest-frame wavelength offset increase (seen from Fig. 4) [11].

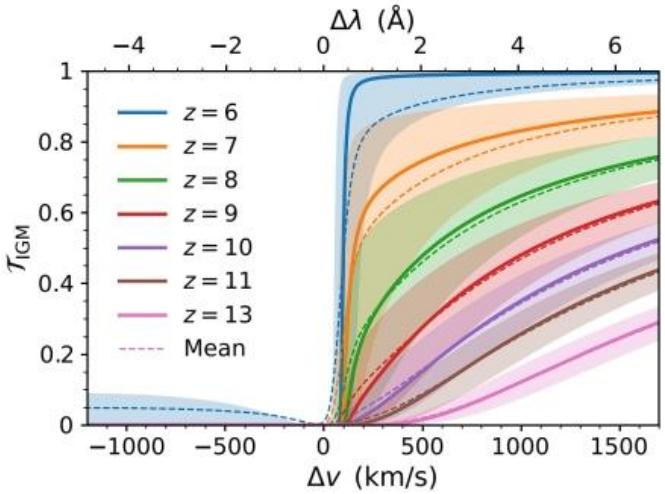


Figure 4. Intergalactic medium transmission as a function of velocity.

Velocity offset is defined as the difference between the center of mass velocity and the centroid velocity, while the Doppler effect accounts for the wavelength offset. A higher redshift accounts for a higher transmission as the velocity offset and wavelength offset increase, and a higher rate of increase in transmission as the velocity offset exceeds zero. This graph successfully illustrates red damping-wing absorption, which originated from the Hjerting-Voight function after the convolution of distribution functions

$$H(x) = \frac{a}{\pi}\int_{-\infty}^{\infty}\frac{e^{-y^2}dy}{a^2+(y-x)^2} \tag{2}$$

The constant an account for the damping, while the damping wing is represented by $a/\sqrt{\pi}x^2$. Finally, the change of the number density of ions as a function of redshift [11]. The results are given in Fig. 5, which accounts for the evolution of photon emission rate.

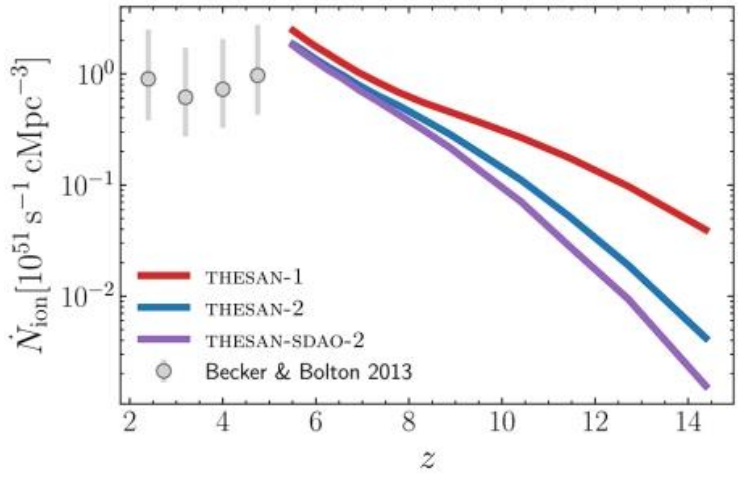


Figure 5. The evolution of the number density of ions decreases as redshift increases for all Thesan simulations.

6. Conclusion

To conclude, in the coding aspect, the Thesan simulation uses the AREPO-RT framework which combines a moving-mesh algorithm with hydrodynamics and dust particle physics and uses live simulation particles for dust and mesh for radiation. Under this technique, the simulations are accurate. For example, the simulation derived that luminosity increases as stellar mass increases while their number density decreases. Another example would be that IGM transmission will increase as velocity offset increases. There are still many limitations like Limited focus on low-z galaxies, Overeximation of galaxy brightness, Insufficient correlation between DTM and redshift, Lack of exploration in other substances, and so on. In the future, The THESAN project may continue to progress knowledge of high-redshift galaxies, enhance the precision of its models, and offer significant contributions to the field of astrophysics by concentrating on these development directions.

Author Contribution

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

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