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Analysis the Functions for James Webb Telescope on THESAN Project

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Abstract:

The THESAN simulation project is a method used to understand the universe. However, the usage of such simulations often requires a lot of computation, complex technology, and high-end equipment, among which James Webb Telescope (JWST) is one of the most important devices in the simulation. The purpose of this study is to analyze and introduce the function and impact of JWST in the THESAN simulation project. First of all, this article briefly introduces the THESAN simulation project and JWST. Then, the study presents the JWST observation mission of galaxy clusters, clusters of galaxies, nebulae and exoplanets in the specific data, as well as the strategy of ERO program in detail. Finally, the paper describes the impact and improvement of the observations made after the JWST launch on the THESAN simulation project and various related data. According to the analysis, these results help stakeholders understand the function of JWST in the THESAN simulation project more quickly.

Keywords: Reflection; JWST; THESAN.

1. Introduction

With JWST (the James Webb Telescope)'s launch [1] and the establish of the THESAN (the suite of large volume radiation-magnetohydrodynamic simulation project) simulation project [2], humanity now combines two of its greatest accomplishments to further test and rectify our understanding of the Universe. JWST, according to a study written by Philip A. Sabelhaus and John Decker, is a follow-on mission after the succeeded Hubble Space Telescope to further the investigation of space. It is incorporated with a primary mirror of 6.5 Meter class segmented, controlled actively, with a nominal temperature of 40o kelvin. With this mirror, it is designed to capture electromagnetic radiations ranging from 0.6 to 28 μm. Other instruments attached on the JWST includes a near-infrared multi-object spectrometer, A Near-Infrared Camera, A Near-Infrared tunable Filter Camera, and a Mid infrared Camera/Spectrometer with the else parts of the JWST, give a combined estimated weight of 6,190 kg, or 13,600 Ibs. The JWST is launched by the Ariane V Expendable Launch Vehicle (TBR), aiming to be located at the 2nd Lagrange point for 5-10 years of mission. It is designed to provide information and data regarding cosmology, the universe structure, the galaxies' origin and evolution, the Milky Way's history and other celestial objects, the star's formation, and the planetary systems' evolution [3].

JWST is a paramount collaborative project between the NASA (National Aeronautics and Space administration), the ESA (European Space Agency), the CSA (Canadian Space Agency), and other teams with its core members including Jane Rigby, Jonathan Gardner, John Mather, Cathy Barclay and others [4]. All the contributors in the JWST program collaborated, generating the synergy of launching and establishing the most powerful astronomical telescope of mankind. The invaluable work founded by them provided us the opportunity here today to collect and summarize the impacts that the JWST observational results have imposed on the THESAN project. Thus, great appreciation is expressed to them. In the following sections of this paper, a more detailed paragraph depicting the various observational results of the JWST telescope is located in the section 'The observational results of JWST' in the later passage of this paper.

The THESAN project, according to the study written by Kannan et. al, is a suite of large volume radiation-magnetohydrodynamic simulation project that aims in the investigation of the reionization changes brought by varying assumptions of the escape fractions, the different matter models, and the convergence of the numbers [2]. The simulation results and variations of the model are then collected and calibrated into realistic histories of reionization. The results of the THESAN simulation are used in the analysis of four sections of contents, the history of reionization, the properties of the galaxies, the effective fractions of escape, and the statistics of the ionized bubble sizes. Specifically, and firstly, the history of reionization includes the evolution of the neutral fraction weighted by volume as a function of redshifts for the THESAN-1, THESAN-2, THESAN-WC-2, THESAN-HIGH-2, THESAN-LOW-2, and THESAN-SDAO-2. Next, the galaxies' properties section includes the stellar-to-halo-mass relations (SHMR, the rate for which baryonic matter are converted by the dark matter halos into stars), the function of quasar luminosity (QLF), and the metallicity-stellar mass relations of the galaxies. Thirdly, the estimation of the fraction of the effective ionizing photons that escaped into the intergalactic medium is included in the third section. Lastly, a full tomographic picture depicting the field of ionization is analyzed in the bubble size statistics section. The THESAN project is considerably important in paving the route for further understanding of the characteristics of the universe. Constructed with an outstanding team including Enrico Garaldi, Rahul Kannan, Araon Smith, and others. All the contributors persevered with incredible intelligence and abiding efforts to give rise to this undoubted milestone in the history of modern astronomy. Their work provided the unparalleled opportunity for humanity to grasp some of the finest details of the universe in an unexpected perspective which is the omniscient viewer, delving into the formative and evolutionary histories of the universe. Thus, great appreciation is expressed to them. In the following sections of this paper, a more detailed paragraph depicting the various simulation findings of the THESAN project is located in the section 'The simulation results of THESAN' in the later passage of this paper [5].

In combination of the two most powerful tools on hands, incalculable researchers have compared the simulation results of the THESAN project with the observatory findings of the JWST telescope in different focuses and perspectives. However, an unfulfilled need within today's research is a study focusing on the collection of their comparative results to offer inspirations and possible guidelines for future research. The significance of this study is a humble trial dedicating to fulfill this unfulfilled need, discussing the finished sections of historical work and providing the essential information to the new generation of researchers. The goal of this paper is to improve the efficiency for future papers' topic selections and avoid possible repetition of research, therefore saving resources and energy for future researchers.

2. Description of JWST and THESAN

THESAN serves as one of the most sophisticated tools accessible for conducting a comprehensive study of the reionizing Universe, providing dependable forecasts regarding a variety of physical quantities associated with both galaxies and cosmic reionization. Moreover, THESAN is an up-to-date set of RMHD cosmological simulations, freshly developed to offer a comprehensive perspective of the early Universe [6]. Specifically, it is engineered to concurrently model the formation of galaxies within the first billion years following the Big Bang, the evolving and spatially non-uniform characteristics of the IGM during Cosmic Dawn and the EoR, and importantly, their connection. THESAN simulates a broad spectrum of physical processes pertinent to the high-redshift Universe. THESAN consists of one flagship run named THESAN-1, which boasts the highest resolution and implements our baseline physical model. Supplemented by a series of additional runs labeled as THESAN-...-2), with a mass resolution eight times lower, THESAN explores diverse options for the escape of ionizing photons, the DM model utilized, and the numerical convergence of the simulations. These additional runs take into account various factors including stochastic star formation adhering to the Kennicut-Schmidt relation, magnetic fields, the return of mass, energy, and metals from supernovae (types of Ia and II) as well as AGB stars, galactic winds, and black holes (including accretion, bi-modal feedback, and radiation output).

The James Webb Space Telescope, abbreviated as JWST, was conceived in the 1990s and 2000s for observing extremely faint objects at near- and mid-infrared wavelengths from the Sun–Earth L2 Lagrange point. Boasting a 6.5-meter aperture and cutting-edge scientific instruments, JWST is grounded in the scientific outcomes of two of NASA's previous flagship missions, namely the Hubble Space Telescope and the Spitzer Space Telescope. On December 25, 2021, the JWST of NASA/ESA/CSA was successfully launched via an Ariane V launch vehicle into a direct-insertion trajectory to L2. Subsequently, JWST was deployed, cooled to its intended cryogenic temperatures behind its enormous sunshield, and its instruments were successfully commissioned and calibrated.

3. Observation Results of JWST

The James Webb Space Telescope's Early Release Observations program, backed by thorough planning and preparation, showcased the advanced capabilities of this novel astronomical observatory by leveraging detailed simulations and incorporating data from earlier missions like the Spitzer Space Telescope. This strategic initiative was not only about employing the technological instruments JWST offers but also about highlighting its exceptional precision and versatility in observing a wide range of celestial bodies and phenomena, thereby showcasing the potential of the telescope to unearth deeper insights into the cosmos than ever before achieved.

A key aspect of the program involved meticulously observing the galaxy cluster SMACS J0723.3-7327, known for its significant redshift of 0.388 [7]. This cluster was selected strategically due to its prominent gravitational lensing effects and its location at a high ecliptic latitude, which substantially reduces zodiacal light interference, thereby improving both the clarity and the quality of the gathered data.The goal was to fully utilize JWST's capabilities, including its NIRCam and MIRI instruments, along with NIRSpec Multi-Object Spectroscopy and NIRISS Wide-Field Slitless Spectroscopy, to capture highly detailed images of high-redshift galaxies. This comprehensive imaging approach aimed to achieve a sensitivity comparable to the deepest observations ever conducted by the Hubble Space Telescope. Specifically, the NIRCam imaging was carried out using a suite of six broadband filters, ranging from F090W to F444W, which allowed the team to achieve impressive imaging depths of approximately AB ~30 mag, while MIRI imaging ventured into the depths of AB ~23 to 26 mag using four distinct filters. Concurrently, the NIRISS spectroscopy targeted the analysis of emission-line galaxies across redshifts from 1.0 to 3.6, and the ambitious observations by NIRSpec aimed at a comprehensive study of 45 galaxies spread across a broad spectrum of redshifts, collectively demonstrating the formidable spectroscopic capabilities of the JWST. A pical results for observation and simulations from THESAN are given in Fig. 1 and Fig. 2, respectively [6, 7].

Another significant target was Stephan's Quintet, a compact group of interacting galaxies featuring an active galactic nucleus (AGN). The observations included an extensive NIRCam mosaic imaging setup accumulating 153.5 M pixels, MIRI imaging of the central galaxies, NIRSpec IFU spectroscopy of NGC 7319's AGN, and MIRI Medium Resolution Spectroscopy focusing on the same AGN. The NIRCam utilized wide filters spanning 0.9-4.5 μm to capture detailed structures ranging from dark dust lanes to emissions from polycyclic aromatic hydrocarbons (PAHs). MIRI's focus was on PAH emissions and tracing star-forming clusters, while the spectroscopy concentrated on the dynamics and composition of the AGN outflows and jet structures. Imaging of the star-forming region NGC 3324, also known as the Cosmic Cliffs within the Carina Nebula, served to exhibit JWST's ability to expose embedded young stars and complex molecular emissions. The observations comprised a four-tile NIRCam mosaic and a five-tile MIRI mosaic. NIRCam was equipped with six filters, each optimized to capture a variety of features such as dust scattering, ionized gases, H2 emissions, and PAH bands. MIRI's filters targeted PAH emissions, the [Ne II] line, and cooler dust emissions [8, 9]. Another significant observation target was NGC 3132, also referred to as the Southern Ring Nebula, which highlighted JWST's capacity to investigate the lifecycle of stars. Imaging of this planetary nebula employed both the NIRCam and MIRI instruments.NIRCam's setup included both broadband and narrowband filters designed to emphasize specific spectral features like hydrogen recombination lines, H2 emissions, and PAH bands. MIRI targeted the 11.3 μm PAH feature, the bright [Ne II] line, and cool dust emissions, providing a comprehensive spectral analysis of the nebula [9].

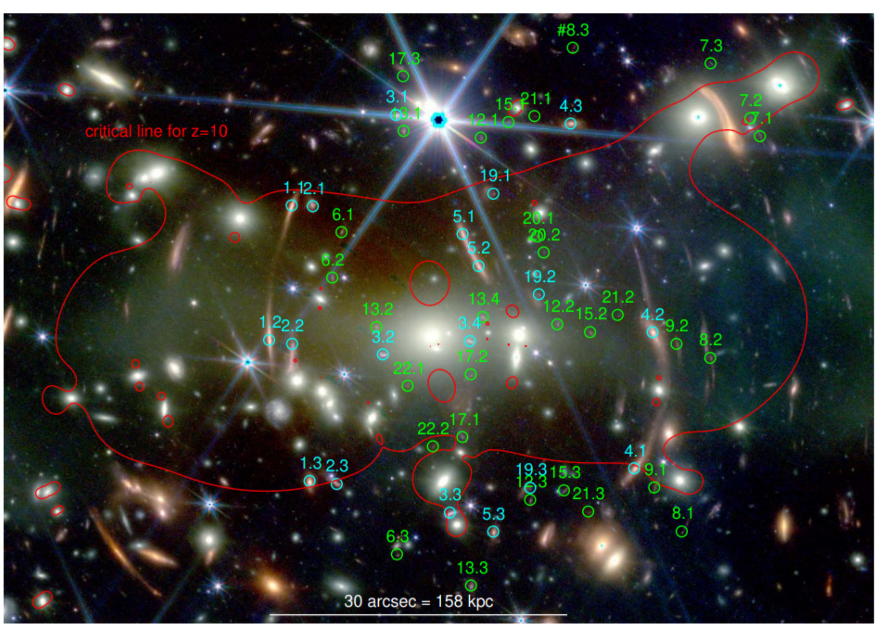

Fig. 1 Observation of SMACS J0723.3-7327 from JWST [7].

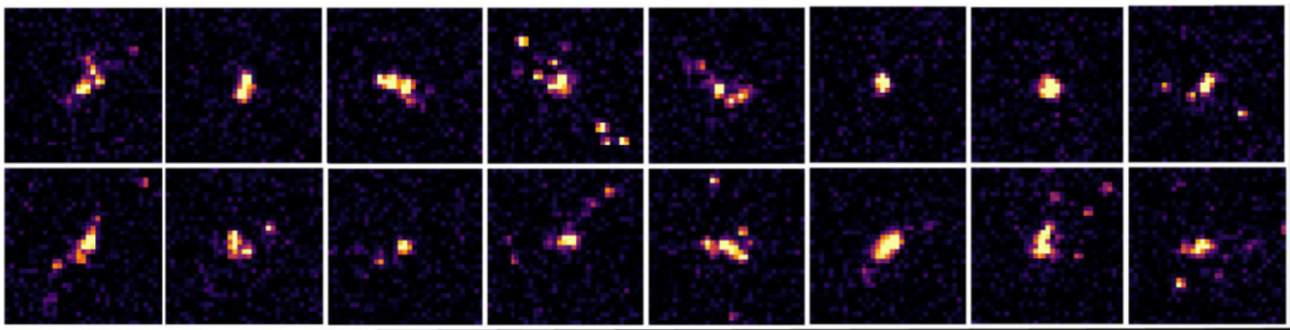

Fig. 2 Simulations of SMACS J0723.3-7327 from THESAN [6].

The exoplanet WASP-96b was observed through NIRISS Single-Object Slitless Spectroscopy to capture a transit event, focusing particularly on the known 1.4 μm water feature previously detected by the Hubble Space Telescope. This observation highlighted JWST's precision in exoplanet studies, enriching our understanding of atmospheric compositions. In terms of observation strategies, the ERO program employed sophisticated techniques such as dithering patterns to enhance image quality and mitigate issues like cosmic rays and pixel defects. Exposure times were intricately calculated to balance sensitivity with the need to avoid saturating the detectors. Filter selections were meticulously chosen to match the specific characteristics and needs of each astronomical target. For wide-area coverage, mosaics with overlapping tiles were used to ensure uniform depth across larger fields of view. Spectroscopic observations were particularly focused on isolating specific emission lines or spectral features of interest [10].

Data processing for the ERO program involved aligning astrometric solutions with Gaia and supplementing these with additional imaging where necessary. Photometric catalogs and redshift estimates were generated for some fields, and background subtraction techniques were employed to refine spectroscopic observations. The JWST Early Release Observations program has effectively highlighted the extensive capabilities of the telescope across a diverse range of astronomical inquiries, laying a solid foundation for future scientific explorations and demonstrating the potential the telescope holds to transform our understanding of the cosmos, thus marking a milestone in the advancement of astronomy. Through these meticulous observations, the program not only showcased the intricate details and phenomena of the universe that JWST can capture but also underscored the pivotal role that such advanced technology plays in pushing the boundaries of space exploration and knowledge [11].

4. Improvements of THESAN

The launch of the James Webb Space Telescope (JWST) marks the start of a new era in astronomical observation, significantly influencing the THESAN simulation project. This project is dedicated to modeling the Epoch of Reionization with great diligence. This era signifies a critical phase in the early universe when the first stars and galaxies ionized the intergalactic medium. The advanced observational tools of the JWST have provided critical data that have led to significant enhancements in the accuracy of the THESAN simulations, fostering a dynamic synergy between groundbreaking observations and sophisticated simulations. This collaboration has notably enhanced the comprehension of the early universe, offering new insights into galaxy formation, probing the enigmatic properties of dark matter, and tracing the evolution of cosmic structures in ways that were previously unattainable.

One of the most notable impacts of JWST observations on the THESAN project is evident in the exploration of alternative dark matter models. Dark matter, an enigmatic and unseen component of the universe, is essential for the formation of galaxies. While conventional cold dark matter models posit that dark matter aggregates through gravitational forces, forming the structural framework for galaxies, alternative models like warm dark matter, interacting dark matter, and fuzzy dark matter propose distinct particle characteristics. These could potentially alter the timing and mechanisms involved in galaxy formation. The observations JWST makes, especially of the faint-end ultraviolet (UV) luminosity function, are pivotal for scrutinizing these alternative models. The phenomenon known as faint-end suppression, which JWST is expected to document, could provide crucial evidence that supports or challenges these alternative dark matter theories. By enhancing our understanding of dark matter's distribution and behavior, data from JWST facilitates a more precise calibration of initial conditions and parameters within the THESAN simulations. This leads to increasingly accurate and reliable models of galaxy formation and evolution.

The James Webb Space Telescope (JWST) has extended our observational and analytical capabilities regarding the intergalactic medium (IGM). This diffuse gas, which fills the space between galaxies, is a critical but elusive component of the universe, significantly impacting galaxy formation and evolution. Through its advanced high-resolution imaging and spectroscopy capabilities, particularly with instruments such as NIRCam and NIRSpec, the JWST has enabled researchers to conduct more nuanced studies of galaxies that are situated in and interact with the IGM. These observations, both direct and indirect, offer deeper insights into various properties of the IGM including its temperature, density, and ionization state, significantly improving our understanding of this medium. The enhanced understanding provided by JWST data has been instrumental in refining the models used in the THESAN simulation, thereby enabling a more accurate depiction of the interactions between galaxies and the IGM during critical periods such as the Epoch of Reionization.

In the realm of high-redshift galaxy research, another pivotal contribution of the JWST to the THESAN project is its capacity to identify and validate candidates of galaxies from the time close to the Big Bang. The ability of the JWST to detect these distant galaxies is crucial for cross-referencing observational data with the predictions made by THESAN simulations. This process of identifying and confirming these early galaxy candidates is vital for ensuring that the simulation's initial conditions are accurate. By verifying the existence of these early galaxies and aligning their observed properties with those anticipated by the simulation, researchers have been able to refine the THESAN model, enhancing its predictive accuracy and reliability in tracing the early stages of galaxy evolution.

Moreover, the JWST has provided indispensable data that enrich our comprehension of the galaxy main sequence—the foundational relationship between a galaxy's rate of star formation and its stellar mass which is essential for understanding the mechanisms that drive star formation throughout the cosmos. The observations made by the JWST across various epochs have allowed researchers to chart the galaxy main sequence with exceptional precision. By juxtaposing these observations with the outcomes from the THESAN simulations, scientists have confirmed the model's effectiveness in reproducing observed trends, indicating a robust alignment between empirical observations and theoretical simulations. This concordance underscores that the THESAN model is adept at capturing the fundamental processes that regulate star formation and galaxy development, thereby affirming its utility as a sophisticated tool for probing the early universe.

The James Webb Space Telescope (JWST) has utilized its advanced multi-wavelength capabilities to provide new insights into both visible ultraviolet (UV) and obscured star formation processes, delivering crucial data for comprehending the comprehensive spectrum of star formation processes. This includes activities hidden within dust-obscured regions of galaxies, which remain elusive to traditional optical telescopes. The rich data JWST collects on variables like star formation rates, gas content, and metallicity enriches researchers' ability to refine existing models of how stars form under varying environmental conditions. This enhanced understanding, particularly of the interconnections between star formation and galaxy properties such as gas metallicity, a vital player in galactic evolution—has become instrumental. Integrating these insights into the THESAN simulations empowers researchers to construct more nuanced models of star formation that encompass the intricate dynamics between gas, dust, and stars during the early universe's formative epochs.

Furthermore, JWST has made substantial strides in studying the mass-metallicity relationship, a crucial correlation that links a galaxy's stellar mass with its metallicity, or the prevalence of elements heavier than hydrogen and helium. This relationship serves as a fundamental diagnostic tool to unravel the mysteries of chemical evolution across galaxies. With its spectral data spanning various redshifts, JWST enables researchers to trace how this relationship has evolved over time. Yet, slight discrepancies noted between these observations and the THESAN simulations have flagged potential overestimations by the simulation in the metal content for given stellar masses. This observation has sparked a deeper examination into factors influencing metal distribution within galaxies, such as the role of cosmic dust and the efficiency with which supernova-driven winds disperse these metals. Addressing these discrepancies will allow researchers to refine the THESAN model, ensuring it more accurately mirrors the complex chemical evolution processes at play within galaxies.

JWST's prowess in detecting and confirming galaxies at redshifts greater than 11 has also opened unprecedented windows into the early universe, offering vivid glimpses into the cosmos's first billion years post-Big Bang. These high-redshift observations are crucial for validating and refining the galaxy formation and evolution models within the THESAN project. By aligning the data gathered from JWST with the simulation's predictions, researchers can ensure that their models authentically replicate the processes responsible for spawning the first galaxies. This iterative refinement process, continually honing the simulation with fresh observational data, significantly boosts the accuracy and reliability of the THESAN model as a tool for probing the early universe.

In summary, the observational data from JWST have profoundly influenced the THESAN simulation project, driving substantial enhancements in the model's accuracy. From refining alternative dark matter models to deepening our grasp of the intergalactic medium, galaxy formation, star formation, and the mass-metallicity relationship, the insights provided by JWST are pushing the frontiers of our cosmic knowledge. Despite some observed discrepancies, the generally strong correlation between JWST observations and the THESAN simulations across a variety of parameters underscores the robustness of the cosmic models utilized in the simulation. As JWST proceeds with its mission, it is set to further refine our understanding of the universe's earliest epochs and improve the accuracy of cosmological simulations such as THESAN [12].

5. Conclusion

To sum up, the James Webb Space Telescope (JWST)'s observatory results have led to profound impacts on the THESAN simulation projects, greatly enhancing our understanding of the early universe. We introduced the observatory results of the JWST telescope and the simulation results of the THESAN project and detailed the data from the early releases of the observational feedback, which focuses on the stellar clusters, galaxy groups, and nebulas, of the JWST telescope. Simultaneously, we've also introduced the observatory strategies of the Epoch of Reionization (EoR). The JWST telescope expanded our capabilities of observing and analyzing intergalactic mediums (IGM) and facilitated further, more detailed investigations regarding the galaxy groups both within the IGM and interacting with the IGM, from which we obtain the observatory results that offer more detailed inspection over the various properties of the IGM, enhancing our understanding in the IGM. As stated in the aforementioned passage, the JWST telescope greatly enhanced the accuracy of the THESAN simulation program, reinforcing the alternative dark matter model and improving the understanding of the IGM, the formation of the galaxies and the stars, via the mass-metality relationships. It is expected that the JWST telescope to be used to improve the accuracy of the THESAN project in other realms of focus, providing more detailed data in the follow-up observations. These results shed light on guiding understanding of the impact that the JWST telescope had made on the THESAN project.

Author Contribution

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

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