Advances in the Study of Ionizing Radiation Escape in Galaxies: Perspectives from Simulations and Observations

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Abstract: The study of ionizing radiation escape in galaxies is crucial for understanding galaxy evolution and cosmic reionization. Ionizing radiation, produced by stars, affects the surrounding interstellar medium by ionizing hydrogen atoms. The escape fraction (fesc) is a key parameter that measures the proportion of ionizing photons that successfully escape, and it directly influences the ionization state of the universe. This study summarizes advancements in simulation and observational techniques, enhancing the understanding of the mechanisms behind ionizing radiation escape. High-resolution simulations (e.g., IllustrisTNG-50 and Thesan-1), have revealed complex structures in hydrogen distribution within galaxies, highlighting the impact of hydrogen ionization state, gas density, and dust content on the escape fraction. Advanced observational tools like JWST and ALMA have provided direct measurements of escape fractions from high-redshift galaxies, validating theoretical models. This research explores various physical factors that influence radiation escape, analyses the limitations of current research, and discusses future research directions in this field, emphasizing the importance of further refined simulations and more accurate observational data.

1 INTRODUCTION

In the past few decades, astronomers have continuously deepened their study of the escape mechanism of ionizing radiation in galaxies through simulations and observations. Ionizing radiation refers to high-energy photons that can ionize hydrogen atoms, typically produced by stars within galaxies, which directly affect the surrounding interstellar medium (Cullen, et al., 2023; Haardt & Madau, 2012). Understanding the escape fraction (fesc) of ionizing radiation is key to studying galaxy evolution because it is directly related to the ionizing influence galaxies have on the cosmic environment (Hopkins, et al., 2023).

Initially, research mainly focused on star formation within galaxies and the distribution of the interstellar medium. However, as simulation technologies have advanced, scientists have gradually discovered that the escape of ionizing radiation is not only influenced by stellar activity and material distribution within galaxies but also regulated by many other complex factors. Contemporarily, with the application of high-resolution simulations such as IllustrisTNG-50, Thesan-1, FIRE-2, and the advent of observational instruments like the James Webb Space Telescope (JWST) and ALMA, scientists can more deeply explore these complex processes (Osterbrock & Ferland, 2006).

In recent years, the development of simulation tools and observational facilities has provided new perspectives for understanding the escape mechanism of ionizing radiation in galaxies. For example, the IllustrisTNG-50 simulation, through high-resolution 3D models, reveals the distribution structure of hydrogen within galaxies, showing a "sponge-like" structure where ionized hydrogen regions are connected through narrow channels, which become crucial pathways for the escape of ionizing radiation (Springel, et al., 2005; Zhang, et al., 2021).

Similarly, the Thesan-1 simulation also provides an in-depth analysis of the evolution of the hydrogen ionization front during the cosmic reionization period, pointing out that the "ionization halo" outside galaxies is crucial for the escape of ionizing radiation.

Furthermore, the appearance of advanced observational instruments such as JWST/NIRSpec and ALMA has enabled us to directly measure the escape fraction of high-redshift galaxies and verify the accuracy of theoretical models. Naidu et al. directly detected the leakage of the Lyman continuum spectrum from the galaxy LEO-1 at z = 8.5 using

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JWST/NIRSpec for the first time, revealing that the escape fraction of this galaxy is as high as 25±5% (Naidu, et al., 2018).

The motivation of this study is to explore in depth the multiple factors that influence the escape of ionizing radiation, particularly the ionization state of hydrogen, gas density, dust content, and others. This paper will combine existing simulation tools and observational data to analyze how these factors interact and jointly influence the escape fraction of ionizing radiation in galaxies. Furthermore, the paper will summarize the limitations of current research and outline the future research directions in this field.

2 DESCRIPTIONS OF IONIZING RADIATION IN GALAXIES

The process of ionizing radiation formation in galaxies can be traced back to the birth and evolution of stars within galaxies. When a star forms and burns hydrogen, it releases large amounts of high-energy photons, which can excite and eject electrons from hydrogen atoms, thereby producing ionized hydrogen (HII). These ionizing photons can freely propagate depending on their energy until they encounter regions of neutral hydrogen (HI), where they are absorbed (Inoue, et al., 2020). Therefore, the ionization state of hydrogen in galaxies directly influences the escape of ionizing radiation (Pillepich, et al., 2021).

3 SIMULATION TOOLS AND OBSERVATION FACILITIES

3.1 Thesan Simulation System

The Thesan simulation system is one of the key tools currently used to study the escape of ionizing radiation (Kannan, et al., 2023). This system not only simulates the transition of hydrogen from neutral to ionized but also accurately depicts the dynamic changes in the ionization front within galaxies. By coupling dark matter, baryonic matter, and radiation transfer, the Thesan simulation reveals the evolution of the ionization front around galaxies, especially its impact during the reionization period.

3.2 IllustrisTNG and FIRE-2 Simulations

The IllustrisTNG-50 simulation provides higher resolution, revealing the "sponge-like" structure of ionized hydrogen regions. Additionally, the FIRE-2 simulation, with its ultra-high spatial resolution, precisely models the impact of supernova explosions on the hydrogen distribution within galaxies, providing important evidence for understanding the variations in escape fractions across different galaxies.

3.3 Observational Facilities

For observational tools, JWST/NIRSpec and ALMA are currently the most advanced instruments. JWST is capable of capturing spectral features from distant galaxies and directly measuring the escape fraction of these galaxies. For example, through JWST/NIRSpec observations, scientists have for the first time detected the leakage of the Lyman continuum spectrum from high-redshift galaxies, thereby obtaining direct data on the escape fraction. ALMA, on the other hand, is primarily used to study the impact of dust on the escape of ionizing radiation by observing specific molecular spectral lines, revealing the influence of dust distribution in galaxies on radiation propagation.

4 DETERMINATION ANALYSIS

Analysis has shown that there are four main factors influencing the escape of ionizing radiation. Research indicates a significant negative correlation between gas density and escape fraction. Specifically, when the density of neutral hydrogen in a galaxy increases, the escape fraction rapidly decreases. This is because higher gas density leads to more ionizing radiation being absorbed by neutral hydrogen, reducing the number of photons that escape. Particularly, when the density exceeds 100 hydrogen atoms per cubic centimeter, the escape fraction typically drops below 1%. The results are given in Fig. 1.

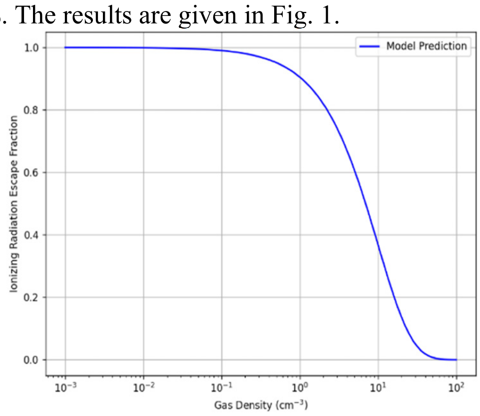

Figure 1: Escape Fraction as a Function of Gas Density (Photo/Picture credit: Original).

The impact of dust on ionizing radiation is reflected in two aspects: absorption and scattering. Dust particles can absorb ionizing radiation, reducing its energy, or alter the propagation direction of photons, thereby decreasing the escape fraction. Studies have shown that when the dust-to-gas mass ratio exceeds 0.3, the escape fraction significantly decreases, especially when dust is concentrated in the core regions of the galaxy, where its impact is even more pronounced. The typical results are given in Fig. 2. The escape fraction of ionizing radiation shows a clear evolutionary trend with cosmic time. During high redshift ($z \approx 8$), the escape fraction of galaxies is typically higher than that of galaxies at low redshift. This trend is closely related to factors such as lower metallicity and dust content, thinner galaxy disks, and stronger star formation feedback as depicted in Fig. 3. The radiation transfer process has significant characteristics of spatial and temporal changes as presented in Fig. 4. On a time scale of tens of millions of years, the escape fraction of a single galaxy may fluctuate by 1-2 orders of magnitude. This fluctuation mainly stems from three physical processes: the instantaneous voids generated by supernova explosions, the random distribution of star formation regions, and the turbulent mixing effect of the interstellar medium. The study also found that the amplitude of this fluctuation is inversely proportional to the mass of the galaxy, which explains why dwarf galaxies usually exhibit a higher escape fraction.

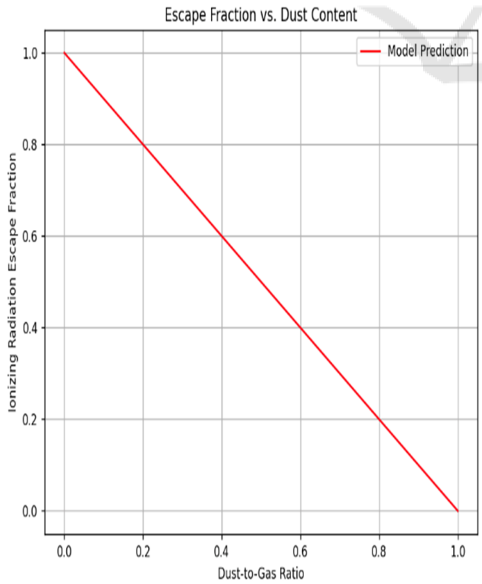

Figure 2: Escape Fraction vs. Dust Content (Photo/Picture credit: Original).

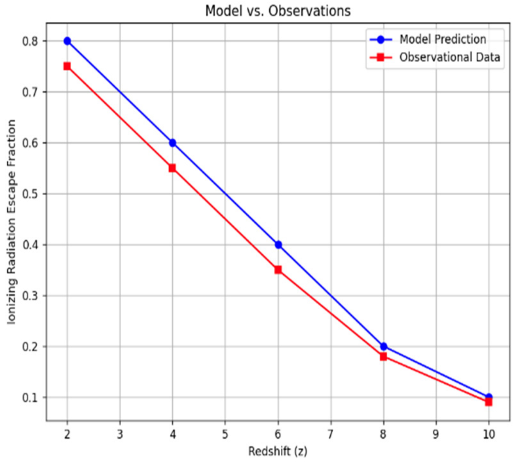

Figure 3: Redshift(z) (Photo/Picture credit: Original).

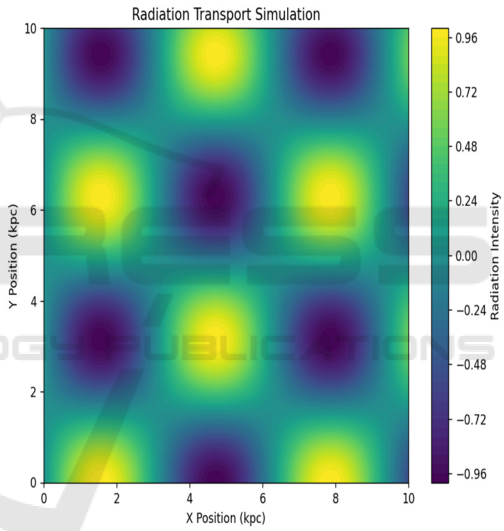

Figure 4: Radiation Transport Simulation (Photo/Picture credit: Original).

5 LIMITATIONS AND PROSPECTS

Despite the significant progress made in the study of galactic ionizing radiation escape, scientists still face several technical and theoretical challenges. The research on ionizing radiation escape involves multiple complex physical processes and a large number of physical parameters, and the interwoven influence of these factors makes a comprehensive understanding difficult. The following will detail the current limitations of the research and look forward to future research directions.

5.1 The Simulation Challenges of Small-Scale Physical Processes

Firstly, one of the major challenges faced by current simulation techniques is the simulation of small-scale physical processes. The process of ionizing radiation escape involves very complex gas dynamics, star formation, supernova feedback, and other processes within galaxies, which often occur at very small spatial scales. For instance, the distribution of hydrogen is not uniform; hydrogen within galaxies often exists in "clumpy" structures. These clumpy hydrogen distributions have a significant impact on the propagation of ionizing radiation. However, due to the complexity of their structures, existing high-resolution simulations still struggle to accurately capture these small-scale physical processes. Especially in regions with high gas density, ionizing radiation is easily absorbed or scattered by neutral hydrogen, leading to systematic errors in simulations.

Furthermore, many current simulation tools, such as IllustrisTNG and Thesan-1, although capable of providing high-resolution simulation results, still have certain limitations when dealing with ultra-small-scale physical processes. These small-scale processes have a significant impact on the escape of ionizing radiation, especially the strong feedback effects produced by supernova explosions. Such feedback can alter the density and temperature of gas, thereby influencing the propagation path of radiation. However, existing simulations still struggle to precisely model these short timescale and small spatial scale dynamic changes.

5.2 Observational Challenges of High-Redshift Galaxies

Another major limitation stems from the constraints of observational equipment. Although modern astronomical devices, e.g., the JWST (James Webb Space Telescope) and ALMA (Atacama Large Millimeter/submillimeter Array), have significantly enhanced our ability to observe distant high-redshift galaxies, there are still certain challenges in capturing the escape rate data of extremely distant galaxies. Observing high-redshift galaxies is quite difficult, partly because these galaxies are extremely far from Earth, and the light signals are severely affected by the redshift effect during transmission, leading to signal attenuation. This signal attenuation not only affects the measurement of the escape rate but also makes it more difficult to obtain high-quality and high-resolution spectral data.

Especially during the high-redshift period ($z \approx 8$ and higher), the escape rate of galaxies is usually high, but due to the weak spectral signals of these galaxies, traditional optical telescopes and low-resolution observation equipment find it difficult to directly measure their escape rates. Therefore, current observational techniques still cannot effectively capture the detailed characteristics of the escaping photons in these high-redshift galaxies, making data quality and resolution the bottlenecks restricting further research in this field.

5.3 Modelling Challenges of Dust Effects

The role of dust in the escape of ionizing radiation is a complex physical process. Although one has relevant theoretical models that can roughly estimate the impact of dust on the escape rate, the large uncertainties in the spatial distribution and physical properties of dust make precise modelling of dust particularly difficult. The influence of dust is not only reflected in the absorption of radiation but also in the scattering effect on the direction of radiation propagation, especially in the central regions of galaxies where dust is dense and the scattering effect is particularly significant. Existing studies mostly rely on simplified assumptions, such as assuming that the distribution of dust in galaxies is uniform, but the actual situation is often much more complex. Therefore, in the simulation of ionizing radiation escape, the role of dust still requires further research and precise modelling.

5.4 Inconsistencies Between Simulation and Observation Result

Although existing simulation tools have made significant progress, there are sometimes certain deviations between these simulation results and observational data. For instance, while the escape rate of galaxies is usually predicted to be relatively low in simulations, some observational results show that the escape rate of some high-redshift galaxies is significantly higher than predicted by simulations. This inconsistency indicates that current theoretical models and simulation tools may have overlooked some important physical factors, and perhaps more observational data are needed to verify these theories. Additionally, the diversity of simulation results also suggests that our understanding of the physical mechanisms of ionizing radiation escape within galaxies is not yet comprehensive.

With the continuous advancement of simulation technology and the advent of next-generation astronomical equipment, one is expected to overcome these limitations and achieve more precise and comprehensive results in future research. Firstly, with the improvement of computing power, future simulation tools will be able to better handle the simulation of small-scale physical processes, especially the dynamic changes of important factors such as hydrogen distribution and supernova feedback. By improving sub-grid models and conducting higher-resolution simulations, one can more accurately capture these small-scale effects and thereby reduce errors in simulations.

Secondly, with the gradual commissioning of next-generation astronomical observation equipment, this study will be able to obtain higher-quality observational data. For instance, the future JWST will provide more detailed high-redshift galaxy data, enabling scientists to directly measure the escape rate and verify the accuracy of theoretical models. Additionally, radio telescopes like ALMA will continue to help us study the impact of dust on ionizing radiation, particularly the role of dust distribution patterns within galaxies in the high-redshift era on radiation escape.

In future research, one also needs to pay more attention to the ionization effect of galaxies on their surrounding environment during the cosmic reionization process. By comprehensively utilizing advanced simulation techniques and observational data, one will be able to gain a deeper understanding of the diversity of ionizing radiation escape mechanisms and further promote the study of galaxy evolution and the formation of large-scale structures in the universe.

6 CONCLUSIONS

To sum up, this research summarizes the current research progress on the escape of ionizing radiation from galaxies, explores the key factors influencing the escape rate, and analyses the limitations of current studies. By integrating simulation tools and observational data, one has gained a deeper understanding of the roles of hydrogen ionization state, gas density, dust content, and other factors in the escape of ionizing radiation. Although significant progress has been made in existing research, there are still some technical and theoretical challenges, especially in the simulation of small-scale physical processes, dust impact modelling, and observations of high-redshift galaxies. Future research will further refine existing models and verify theoretical assumptions through more precise observational data. The study of ionizing radiation escape is not only crucial for understanding galaxy evolution and the reionization process of the universe but also provides important clues for exploring the formation of large-scale structures in the universe. With the continuous development of simulation technology and the advancement of astronomical observation equipment, one has every reason to believe that the study of ionizing radiation escape will achieve more in-depth and accurate results in the future.

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