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The contribution and role of low- and high-mass galaxies in the Epoch of Reionization

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Abstract. Knowing the contributions and roles of both high- and low-mass galaxies during the epoch of reionization is crucial for comprehending the early cosmos and the galaxies formed in the early days of the universe. Historically, research on this topic was limited by technological constraints such as the viewable time domain of telescopes. However, technological advances and state-of-art facilities including the successful functioning of the James Webb Space Telescope (JWST) and the introduction of modern large-scale galaxy simulations have substantially improved this perplexing scenario. With this in mind, this study defines high- and low-mass galaxies during the reionization epoch and discusses how they contribute to this period in the universe's early history. The analysis introduces both the current results of astrophysicists and the limitations of scientists' research in this area. Overall, these findings show that early galaxies in the high-redshift universe are a topic with much research potential and shed light on guiding further exploration of the reionization in the universe.

Keywords: high-shift, reionization, formation, dark ages, observational cosmology.

1. Introduction

The formation of galaxies is crucial in our understanding of the universe's development [1]. Although there's a general agreement that galaxies were created from primordial fluctuations through gravitational instability in the expanding matter background, more physical processes need to be comprehended and applied in theoretical models to interpret observations accurately. Recent advances in identifying galaxies that formed shortly after the Big Bang have heightened the need to conduct more advanced and comprehensive studies of early frameworks [1]. Astrophysicists seek to integrate data from many theoretical models or research in this review to produce a coherent representation of the universe in its initial conception. This involves the study of star formation as well as the effects of early architecture on large universe networks with enormous scales such as cosmic reionization and intergalactic metal richness [2]. With that in context, it could be argued that understanding the process of galaxy formation from the beginning to the present is a major objective in astronomy. Observations of both current and early galaxies are necessary to accomplish this, but data on early high-redshift galaxies, including the first galaxies, is currently unavailable [2].

The period of reionization in cosmic history is little understood due to the difficulty of detecting such a remote time and the challenges connected with theoretical inquiries [1]. Understanding this epoch, however, is crucial because it connects the high-redshift Universe to the galactic structures one sees today. By investigating reionization, scientists can acquire insights into the origins of galaxies and put their knowledge of the physical processes involved in elliptical galaxies, which have primarily been derived from local observations, to test [3].

Large telescopes have allowed the observation of millions of galaxies up to a redshift of about 10 in the last 20 to 30 years. Deep-field imaging, such as the Hubble Deep Field project, has permitted the identification of galaxies with a limit of around 30 mags in the wavelength range of 0.4-1.6 m in the Hubble Ultra Deep Field(HUDF) utilizing the Advanced Camera for Surveys(ACS) and Hubble's Wide Field Camera 3(WFC3) instruments with the Hubble Telescope [4]. After the launch of the JWST, the detectable temporal range for deep space has been substantially expanded. After being launched at the end of 2021, it became operational in early 2022. On July 12, 2022, the first JWST data sets were provided as part of the observations that were initially released to the world. Also named the ERO (Early Released Observations), the data set targeted a huge cluster dubbed SMACS J0723.3-7327 (SMACS J0723, z = 0.39) and Stephan's Quintet. The imaging data is vast enough to discover the galaxies that are formed in the early universe with depths of around 30 mags using NIRCam (Rieke et al. [4]), while multiband data covering wavelengths of more than 2 m allows the detection of galaxies at hitherto inaccessible redshift ranges, up to about z = 20 [4].

Scholars working on the THESAN project discovered that their galaxy formation model is consistent with a variety of high-redshift observations, such as the relationship between planetary mass and the mass of halos, the distribution of galaxy stellar mass, the star formation rate, and the relationship between mass and metallicity [5]. Despite that, the model was mostly optimized using observations with a redshift of 0. They also show that alternative reionization models yield varied bubble size distributions, which produce distinct signals in the 21 cm emission, particularly at large spatial scales [5]. These findings will help future 21 cm investigations pinpoint the origins of the budget of photon ionization. The MERAXES simulation project, on the other hand, focuses on galaxy formation during the reionization epoch. The MERAXES model is intended to investigate galaxies' growth during reionization [6]. It is unique in that it comprises a reionization treatment that is both temporally and spatially connected. It is based on a bespoke 100 Mpc3 N-body model with high mass and temporal precision, enabling researchers to capture the relevant physics of constellations and galaxy clusters during primordial galaxy evolution [6]. The supernova feedback-integrated fiducial updated and maintained the visual depth to conduction electrons and expansion of the galactic star mass function between redshifts 5 and 7, indicating that a wide range of halo masses assist in reionization. Even with a fixed breakout fraction and global electron affinity, it is difficult to match the stated ionizing emissivity for redshifts smaller than z=6.

This study will discuss the current and future state of research into how the high- and low-mass galaxies have contributed to the reionization epoch. It is inspired by the possible areas of inquiry indicated on the official website of the THESAN project. The following is the outline for this paper. In Sections 1 and 2, the author will describe the Epoch of Reionization and explain how high-mass and low-mass galaxies are determined within such a time span. The author will then address the role and contribution of low galaxies in Section 3. The author will examine how high-mass galaxies contribute to the reionization of the universe in Section 4. Section 5 will be the conclusion of this investigation.

2. General galaxy information in the Epoch of Reionization

The Universe's Epoch of Reionization signals the end of its historical period of dark ages with the emergence of the first generation of galaxies. These early galaxies begin to radiate UV light, causing ionized zones to form around them. When additional ionizing radiation sources appear, the proportion of ionized gas in the Cosmos increases rapidly, leading eventually to the total ionization of hydrogen. The Epoch of Reionization refers to the transition of the Universe from neutral to ionized [7]. Deep imaging and spectroscopy can be provided by the Webb Telescope (JWST) for sources with redshifts larger than 6, covering the whole Epoch of Reionization (EoR) from 6 to 10 [7]. This feature allows for an in-depth examination of the nature of many sources over the first hundred million years of the Universe's existence. The Medium Resolution Spectrograph (MRS) on the JWST's mid-IR Instrument (MIRI) can monitor the optical emission spectrum H and [OIII] 0.5007 m at redshifts greater than 7 and

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9 [8], correspondingly. These observations would provide vital insights into the physical characteristics of sources throughout the early stages of the EoR.

In the Epoch of Reionization, scientists are currently employing a variety of characteristics to identify high-mass galaxies from minimal galaxies. The most utilized include luminosity, size, stellar population, star formation rate, and so forth. This study will introduce five factors that define both high- and low-mass galaxies.

1 1 Luminosity: High-mass galaxies are typically more luminous than low-mass galaxies, meaning they emit more light. This is because they contain more stars, which generate more light through nuclear fusion.

1 2 Size: High-mass galaxies have larger sizes compared to low-mass galaxies. This is because they have more matter and a stronger gravitational pull, which allows them to attract more gas and dust and form more stars.

1 3 Star formation rate: High-mass galaxies typically have a higher rate of star formation than low-mass galaxies. This is because they have more gas and dust available to form stars.

1 4 Metallicity: High-mass galaxies tend to have a higher metallicity (i.e., a higher proportion of heavy elements such as carbon, nitrogen, and oxygen) than low-mass galaxies. This is because they have had more time to synthesize these elements through stellar nucleosynthesis.

1 5 Central black hole mass: High-mass galaxies have larger central black holes than low-mass galaxies. This is because the mass of the black hole is tied to the mass of the galaxy's bulging, which is proportional to the total mass of the galaxy.

The definitions of high-mass and low-mass galaxies are now significantly depending on the objective of the research. As a result, there is no established universal rule governing what counts as high-mass galaxies and what does not. As a result, the definitions of high-mass galaxies and low-mass galaxies are defined by the author based on the research topic and may differ from those in other research publications.

According to solar masses, a low-mass galaxy can be defined as a galaxy with a total mass of less than or around 108 solar masses. In terms of luminosity, in general, for the EoR, a low-mass galaxy can be defined as a galaxy with a low UV luminosity, typically below 10^{41} erg/s, which corresponds to means that a few solar masses of stars form per year [9]. This definition is based on the idea that low-mass galaxies are less efficient at forming stars than more massive galaxies, due to their lower gas content and weaker gravitational potential [9].

A high-mass galaxy can be defined as a galaxy with a total mass of more than or around 108 solar masses. According to luminosity, for example, in the ultraviolet (UV) or blue wavelength spectrum at rest, a galaxy with an absolute magnitude of -20 or brighter could be considered a high-mass galaxy, as this is roughly the characteristic luminosity of star-forming galaxies with masses above 108 solar masses. In the rest-frame optical wavelength range, a high-mass galaxy could be defined as one with an absolute magnitude of -22 or brighter, which corresponds to the characteristic luminosity of massive galaxies with masses above 1011 solar masses [10]. It's worth noting that the precise definition of a high-mass galaxy using luminosity can vary depending on the specific study or context, and it's important to consider the relevant wavelength range and bandpass when making such a definition. For instance, in Figure 1, the graph depicts the distribution of star masses at various redshift intervals in three distinct regions: Rarepeak on the top left, Normal on the top right, and Void on the bottom left. Redshift intervals are 15-20, 13-20 (including 12.5), and 8-15. The distribution of star masses across all areas and redshift intervals is presented in the lower right panel. The colorful lines on the graph represent the redshifts that are most similar throughout the regions shown in the legend.

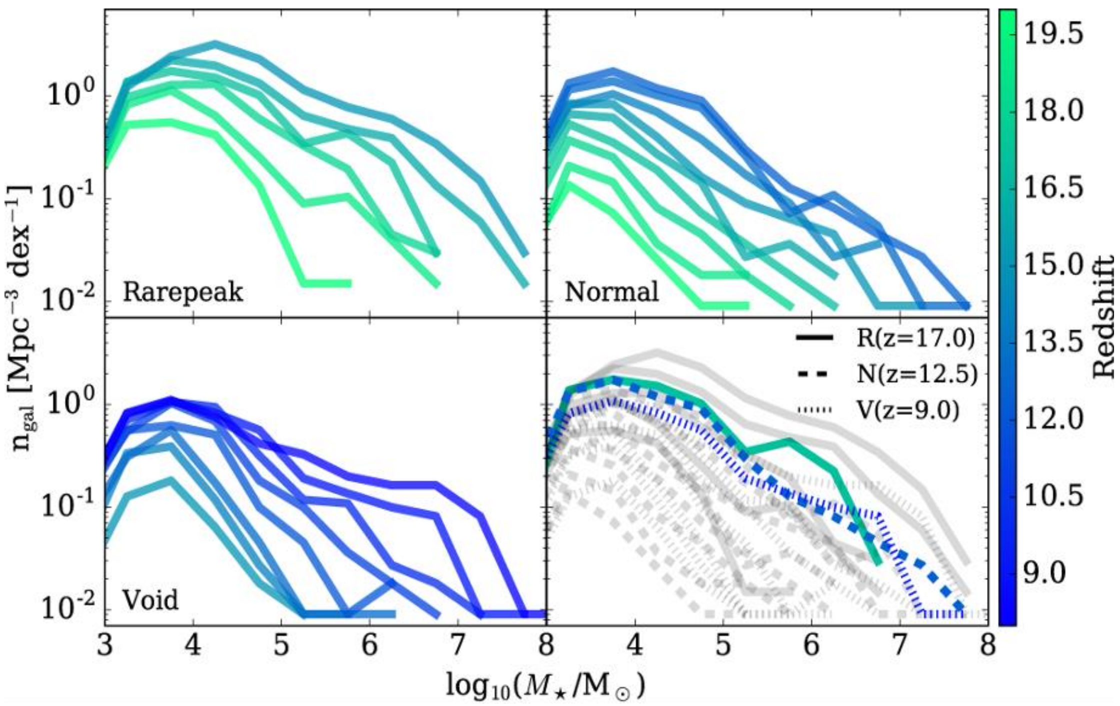

Figure 1. Star masses at various redshift intervals in three distinct regions.

3. The role and contribution of the low-mass galaxies in the EoR

According to one proposal, low-mass galaxies at z=6 provide the initial sources of hydrogen ionizing photons required for reionization to be completed [11]. These small-scale galaxies are difficult to identify with existing telescopes because of their distance and natural dimness, resulting in low signal-to-noise ratios. Recent observational investigations, for instance, the HUDF campaigns in 2009 and 2012, have provided vital insights into the essential composition and characteristics of the early galaxies and their significance in the process of reionization. These studies looked at galaxies with lighting range UV magnitudes as low as 18 at the redshift of z 7 and as high as 11 at that of z 11 [11].

As shown in Figure 1, the UV ionizing photons produced by "bright galaxies" detected thus far are inadequate to entirely ionize the cosmos by z = 6, as anticipated by quasar data, as illustrated in Figure 1. As a result, more ionizing sources, such as fainter galaxies and accreting black holes, are needed to provide the remaining ionizing photons [11]. Robertson extrapolated the UV luminosity function (LF) and demonstrated that it must extend to MUV 13 to match the Planck satellite's measured integrated Thomson optical depth es = 0.066 0.012. These galaxies might have stellar have low stellar masses in halos with masses as large as M~108 MΘ, and their ultraviolet radiation would be adequate to completely finish and sustain reionization. Additionally, the calculation error in es shows that there may be some input from star formation in M ≤ 108 MΘminihalos [11].

The birth, expansion, and demise of massive stars release enormous quantities of energy and momentum into the gaseous atmosphere around the regions where stars are forming [12]. This feedback process limits new star formation by either expelling gas from the galaxy or overheating the environment so that new stars can no longer form. Feedback appeared as galactic-scale gas fluxes, notably in the early Universe when galaxies had high rates of star formation [12].

4. The contribution and role of high-mass galaxies in the EoR

The ionizing radiation produced by high-mass galaxies during the epoch of reionization was able to penetrate the neutral hydrogen gas and ionize it, creating ionized bubbles in the intergalactic medium [13]. These ionized bubbles eventually grew and merged, leading to the complete reionization of the universe. High-mass galaxies played a significant role in this process because they were able to produce a large amount of ionizing radiation due to their high star formation rates and the presence of massive stars that emit a lot of ionizing photons [13]. These galaxies were also more likely to be in regions with a higher density of neutral hydrogen gas, which meant that they had a greater chance of ionizing nearby gas and contributing to the growth of ionized bubbles. The impact of high-mass galaxies in the reionization era is still being researched, and scientists are continuing to investigate the features of these galaxies and their impact on the reionization process [14]. Knowing the role of high-mass galaxies in reionization is critical for understanding the universe's development and the birth of the earliest galaxies.

5. Conclusion

In summary, both high- and low-mass galaxies obviously contribute to the reionization of the universe by either providing hydrogen ionizing photons or producing an abundance of ionizing radiation. Low-mass galaxies contribute to the reionization process by supplying UV ionizing photons, which are required to complete and sustain reionization. Minihalos also contribute to the creation of stars in the early galaxy. High-mass galaxies, on the other hand, contribute to the reionization process by emitting massive amounts of ionizing radiation during the reionization epoch. High-mass galaxies have a greater possibility of contributing to the creation of ionized bubbles because they are more likely to be found in locations with appropriate amounts of neutral hydrogen gas.

Overall, the study of galaxies of both low stellar mass and high stellar mass during the reionization epoch is relatively constrained to observational techniques. There are few resources on the evolution and role of galaxies during this time period. By examining Google Scholar, the author finds no research that is directly related to high-mass galaxies, indicating the future study potential of this topic. Knowing the role and contribution of galaxies is critical to further developing the genesis and universe’s evolution and its initial galaxies. Previous observational research, on the other hand, has been severely hampered by physical equipment. Even if the JWST's operation brings back data that scientists have never been able to gather before, there is still a long way to go before further details about deep space galaxies are exposed to the globe. In a more positive light, new cutting-edge supercomputer models are being developed to enable the study of high-redshift galaxies. Yet, researchers must continue to combine theoretical discoveries with empirical observation. More astrophysicists will be needed in the future to investigate the attributes of early galaxies.

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