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The Contribution of Low- and Intermediate-mass Galaxies in the Universe at the Epoch of Reionization

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Abstract:

Understanding the contribution and role of low- and intermediate-mass galaxies in the universe at the Epoch of Reionization (EoR) is pivotal to exploring and discovering further the specific era when the earliest galaxies formed and reionized the inter-galactic medium (IGM). Through more advanced technical support (especially for the observable telescopes) from century to century, a more detailed explanation of this topic can be demonstrated, even if it is still restricted currently. Nevertheless, some state-of-the-art equipment and mature functioning facilities, including the James Webb Space Telescope (JWST) that update the discovery, the THESAN project that simulates the changes at the EoR, and other institutes or projects that enhance the observable standard and attention in the puzzled circumstances (e.g. high-redshift universe). Considering all these accounts, this study investigates the contribution of low- and intermediate-mass galaxies in the reionization era. It delves into their dedication and characteristics to this idiographic epoch in the preliminary stage of the universe. The explanation and findings are in light of the updated results in the field of astrophysics, the restrictions in the current puzzle, and the further looking in the developing scenario. They substantially offer invaluable fresh insights and lay a solid foundation for the further exploration of the cosmological effects during the EoR.

Keywords: Epoch of reionization, star formation, morphological evolution, low-mass, intermediate-mass

1. Introduction

The Epoch of Reionization (EoR) acts as a vital part of cosmic history, likely believed to have been triggered by the appearance of the first stars and galaxies. Its process involves the transformation of the neutral hydrogen, which is mostly situated outside of galaxies in an IGM into an ionized state [1]. Even though currently there are some hypotheses for astrophysicists in the formation of the earliest galaxies, constructing a comprehensive model poses a significant challenge as researchers strive to align their observations of galaxies in the current or nearby universe with those from the early universe, as well as with theoretical simulations. Among these, the formation and evolution of early galaxies and stellar during the EoR can be connected to the research on the influence of the early universe's structure such as the ionizing radiation from the early universe, the galaxies' gas and dust properties, and some heavy elements' production enrichment like metals, galactic winds and IGM at the EoR. By considering all the elements above, it is pivotal to understand and delve into the development and evolution of galaxies in the fields of cosmology, astronomy, and astrophysics as they represent the main objective and development direction among all fields above. However, since the observational process in this objective is crucial to consider, the understanding of the development of galaxies is still in the fog due to the lack of data collection and research material on determining high-redshift galaxies.

Since the high requirement and challenging detection for the process of formation and evolution of the galaxies at the EoR, fewer people have a deeper understanding of this period (approximately in a range of 400 million to 1 billion years after the Big Bang) in cosmic history. Nevertheless, it can be argued that this period is still becoming more significant as the high-redshift galaxies, including the early galaxies, can be associated with star formation and galaxy morphology in the present-day galaxy model. Through investigating the EoR, the formation of cosmic structure, the early universe's physical condition, and modern galaxy morphology (spiral, elliptical, irregular, etc.) are more understood.

Some projects and telescopes worldwide had valuable observations in various redshift (z) values. James Webb Space Telescope (JWST), for example, has provided remarkable insights into high-redshift galaxies by detecting redshifts more than 10. One of the preliminary research papers grounded in JWST identified a galaxy that appeared unusually bright and located at a great distance, initially named GLASS-z13 (Naidu et al.), indicating that the apparent distance at z=13. The redshift of the galaxy was subsequently adjusted to 12.4 and reclassified to GLASS-z12 [2]. Other telescopes, like the Hubble Space Telescope (HST), had groundbreaking discoveries such as the detection of galaxies like GN-z11 at z=11.09. This galaxy, discovered prior to the launch of JWST, held the distinction of being the farthest-known galaxy at the time of its discovery, thereby offering a vantage point into the universe about 13.4 billion years in the past, 400 million years after the Big Bang [3].

Besides, researchers working on the THESAN project provide a thorough analysis of galaxy sizes at $z \gtrsim 6$, rooted in its simulations. They have conducted an investigation into the physical mechanisms that control the angular momentum transfer in galaxies and the processes driving compaction in massive galaxies and found a notable inconsistency between the galaxy size predictions of THESAN and the actual observations, particularly evident at the lower mass and faint end [4].

The forthcoming study aims to explore the previous, current, and prospective state of research concerning the impact of low- and intermediate-mass galaxies on the EoR, drawing inspiration from the projects (THESAN) or telescopes (JWST, HST, etc.) worldwide. The paper will be structured as follows:

Sections 1 and 2 will provide an overview of the EoR and elucidate the processes driving galaxies' formation and morphological evolution. The low-mass galaxies' pivotal role and contributions will be delved into in Section 3.1, and then the intermediate-mass galaxies' significant contributions to the EoR will be thoroughly examined in Section 3.2. Section 4 will encapsulate the findings and serve as the conclusion of this inquiry.

2. General Galaxy Formation and Morphological Evolution in the EoR

2.1 The Formation of Galaxy

Understanding the process of galaxy formation during the reionization period necessitates a well-rounded examination of the transition of neutral hydrogen. Neutral hydrogen predominantly resides outside of galaxies within the IGM in a neutral state. Approximately 370,000 years after the Big Bang, the universe emitted radiation that in the current period can be observed as the cosmic microwave background (CMB) [1]. Following the Big Bang, the universe was characterized by a hot, dense plasma of matter and radiation. Subsequent to the expansion and cooling of the gas, protons commenced capturing free electrons, leading to the formation of atomic hydrogen. Then, the epoch was followed by a period of darkness devoid of new sources of visible light. Over hundreds of millions of years, the gravitational forces amplified minor density irregularities that were presented since the Big Bang, which eventually culminated in the initiation of star and photo-galaxy formation [5].

The interaction between dark matter and baryonic matter can be directly associated with early galaxy formation. Dark matter had an important effect in preserving the pre-

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liminary irregularities in cosmological density on the scale of galaxies. These irregularities within baryonic matter were mitigated through momentum transport (the viscosity) subsequent to the decoupling of radiation from baryons during the initial few hundred thousand years following the Big Bang. The early formation of dark matter halos contributed to the genesis of observable galaxies, even at high redshifts ($z>6$). Dark matter halos are responsible for most of the gravitational pull that allows stable structures to form in the universe. While the fluctuations in the universe expanded due to gravitational instability over time. In the preliminary stage, gas and dark matter were evenly distributed. When the universe progressed, the gas dissipated and gravitated toward the centers of dark matter halos. For some dark matter halos that are enormous enough, the process for formation can be considered as the gas-cooled, star formed, and a protogalaxy took shape [8]. In addition, dark matter halos have facilitated the sustenance of galaxies, groups, and clusters; on the other hand, dark energy has led to the disintegration of unbound structures and the expansion of space between bound structures, such as the Local Group of galaxies [6].

Following the formation of galaxies, the energetic processes within them have a significant impact on their immediate environment through diverse forms of feedback, accordingly impacting the future accretion of gas and the formation of stars. In this context, it is evident that the growth, internal characteristics, and spatial distribution of galaxies are intimately interconnected with the growth, internal characteristics, and spatial distribution of dark matter halos [7]. Therefore, galaxies' existence and prospective development owe much to dark matter.

2.2 Galaxy Morphological Evolution

The difference in redshift reflects the deviation in different galaxies. In the distant universe, the morphology of galaxies began to noticeably change compared to nearby galaxies at redshifts as low as $z=0.3$, corresponding to a period of 3.5 Giga year (Gyr, which is equivalent to a period approximately 3.5 billion years ago), representing only 25% of the present age of the universe [8]. In terms of higher redshift like $z=0.5$, which is 5Gyr (5 billion years ago), spiral arms exhibited reduced definition and increased disorder, and there was a potential decrease in the prevalence of barred spiral galaxies.

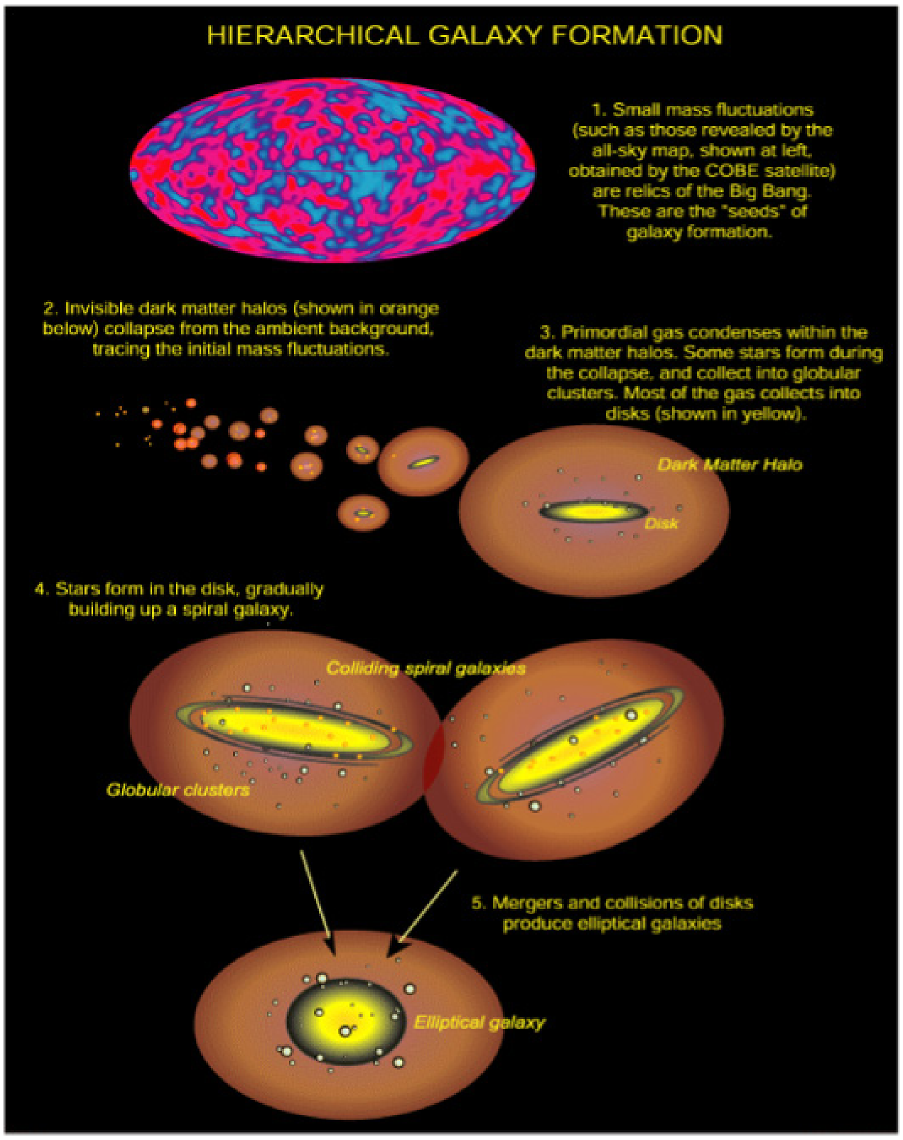

Fig 1. The hierarchical galaxy formation [8]

In Section 2.1 the author mentions the concentrations of dark matter formed and its connection to the galaxy formation. This also acts as a hypothesis theoretically in focusing on the gravitating of the dark matter. In the conceptual framework above (Figure 1), modicum concentrations of dark matter initially exhibit gradual growth, thus undergoing compaction by their gravitational pull. Upon reaching a critical density of approximately a multiple of 200 in the average background density of the universe then undergoes a sudden non-linear collapse, culminating in the formation of an extensive dark matter halo. In our contemporary comprehension of galaxy formation, it is understood that each galaxy forms and develops in a dark matter halo, the formation and expansion of galaxies over time are intricately linked to the expansion of the halos in which they originate [7]. Over time, these halos merge under the influence of mutual gravitational forces, fusion to engender a hierarchy of larger halos. Then, the cooling rate of hydrogen gas within these substantial halos dictates the progression of standard galaxies and their morphological evolution extensively [8]. The spiral galaxy is built by the formed stars in the disk, which then contribute to the morphological evolution between the spiral shape and the elliptical shape through the process of merging and collisions.

3. Contribution of the Low- and Intermediate-mass Galaxy in the EoR

Different mass galaxies have distinctive interpretations. The low-mass galaxies can be defined by some galaxies that contain relatively small-mass stellar, which are con-

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sidered to be lower than 10^9 solar masses ($M_?$). Whereas the high-mass galaxies represent the galaxies that are at the galaxy mass $10^{10} M_?$, and the intermediate-mass in the range $10^9 M_? \leqslant M \leqslant 10^{10} M_?$. Moreover, the discrepancy of mass halo in different mass galaxies also reflects the evolution and influence of galaxy at the EoR.

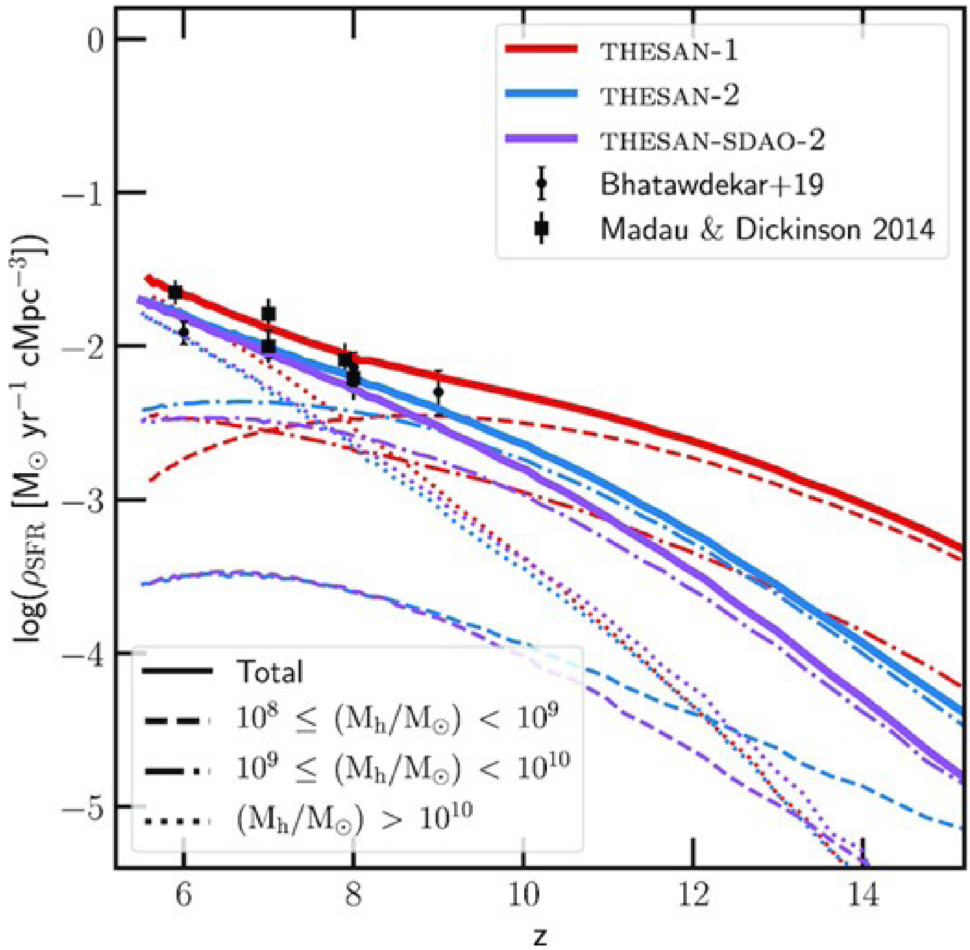

Fig. 2 The simulation for star formation rate density in different redshift and mass halos [5]

Figure 2 above illustrates the progression of the star formation rate density (SFRD) in different cosmic periods (mostly covered from z=6 to z=14) in the THESAN-1 (plotted in red), THESAN-2 (plotted in blue), and THESAN-SDAO-2 (plotted in purple) models [5]. In detail, the dashed line corresponds to the intermediate-mass halos, which exhibit a substantial contribution in a broad range of redshifts ($6 < z < 14$). The comparatively slower decrease in SFRD for this mass range can be inferred that the intermediate-mass galaxies consistently facilitated star formation during this era. Conversely, the solid line represents low-mass halos and their role in the SFRD is in the prominent status at the higher redshift ($z > 8$).

3.1 Contribution of the Low-mass Galaxies

As shown in Figure 2, a distinct pattern emerges regarding star formation within low-mass halos across the three runs. Notably, above z>8, THESAN-1 indicates that majority of the star formation emerges within these low-mass halos, contrasting with their lesser significance in other runs. This discrepancy arises from the incapacity of THESAN-2, which is incapable of accurately representing low-mass halos, consequently leading to a diminished contribution to the star formation rate in general [5]. In addition, these results, in a way, do reflect that the THESAN-SDAO-2 simulation's capacity to suppress low-mass galaxy formation results in a notably low standard of star formation within these halos.

Furthermore, it is postulated that low-mass galaxies at redshift z~6 serve as the principal sources of hydrogen ionizing photons required for the process of reionization.

These galaxies exhibit low signal-to-noise ratios when observed due to their significant distance and inherent dimness [9]. In this context, the Ultradeep NIRSpec and NIRCam ObserVations before the Epoch of Reionization (UNCOVER) program (#2561) arose, which is an international consortium of astronomers leveraged gravitational lensing by the cluster Abell 2744 to study these distant sources [10].

The team's investigation unveiled that these faint galaxies are substantial emitters of ultraviolet light (UV), exceeding previous assumptions by a factor of 4. This suggested that the majority of the photons responsible for reionizing the universe likely originated from these dwarf galaxies. This discovery emphasizes the significant contribution of ultra-faint galaxies in the early universe's evolution. They generate ionizing photons that catalyze the transformation of neutral hydrogen into ionized plasma during EoR, underscoring the significance of the behavior of low-mass galaxies in the universe's history [10].

3.2 Contribution of the Intermediate-mass Galaxies

In the three models in Figure 2, the SFRD at particularly high redshifts is predominantly influenced by medium-mass halos. It is worth noting that simulations have shown a decrease in the star formation rate (SFR), particularly in the intermediate- and low-mass halos, as reionization progresses [6]. This phenomenon is likely attributed to the photoheating feedback resulting from the reionization process, which serves to restrict the accretion of gas onto these diminutive halos.

Additionally, the mass and distribution of intermediate-mass galaxies are closely connected to the formation and evolution of morphology framework in the universe [11]. These intermediate-mass galaxies, while less numerous than low-mass galaxies, possess a greater gravitational potential, which allows for the retention of gas and the facilitation of SFR in a more efficient manner. Whereas their role in the universe at the EoR is minor in contrast to the low-mass galaxies, their contribution cannot be neglected in pushing forward the reionization process to an advanced scale at the later stages at the era of reionization.

4. Summary

To sum up, both low- and intermediate-mass galaxies notably exhibit a significant contribution in the reionization of the universe. This is achieved through abundant production of ionizing radiation or the possession of a gravitational potential. The reionization process is initiated by low-mass galaxies, which produce ionizing photons early and in large quantities. Subsequently, intermediate-mass galaxies sustain this process through their higher efficiency in the star formation process at the relatively lower redshift. Taking both into the collection, these galaxies are instrumental in the transformation between the state of neutral hydrogen, ionized radiation, and transparent cosmos. Furthermore, the low- and intermediate-mass halos also signify the formation of stars and the morphological evolution of distinct galaxies.

In reflection, this investigation on the contribution of both low- and intermediate-mass galaxies at EoR is generally constrained in the dependency and limit of simulation. Although some simulations like THESAN and IllustrisTNG have provided valuable insights into galaxy formation during the reionization period, these models are limited as they rely on feedback mechanisms, such as the stellar winds, which still get restrained in observation. Most importantly, the scarcity of direct observational data, particularly at a high redshift at z>8, has been a significant challenge in understanding early galaxy formation. After the launch of JWST, our understanding and thinking depended heavily on the interpretation and analysis of low-redshift data and, in some cases, from observing telescopes (like HST) and simulation models such as THESAN and IllustrisTNG.

Additionally, the literature on this topic is relatively sparse, particularly in intermediate-mass galaxies. On the optimistic side, however, this scarcity of literature and data presents ample opportunities for further development in this field. Advancements in supercomputing and gravitational lens technologies are gradually addressing the challenges grounded in luminosity adjustment, redshift measurements, etc. The aforementioned limitations and reflections have also spurred generations of astronomers and astrophysicists to persist in pursuing this course of inquiry.

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