The Mass-Size Relation of Galaxies in Varied Environments

Shojaei, Mohammadreza[1]; Tavasoli, Saeed[1]; Ghafour, Parsa [1]

[1] *Physics Department, Kharazmi University, Tehran, Iran;* mohammadreshojaei@gmail.com

Abstract

We investigate the stellar mass-size relation of galaxies, as well as their specific star formation rate (Ssfr), in both high-density and low-density environments. The study is based on data obtained from the Millennium simulation in z=0. According to our research, the size of massive elliptical and spiral galaxies is not affected by their environment. Due to the effects of ram pressure stripping and gravitational interaction, massive spiral galaxies tend to have lower star formation rates. The size of low-mass spiral galaxies is affected by dense environments, resulting in larger sizes in voids. Our analysis indicates that the abundance of cold gas has a greater impact on star formation rate than the halo mass of galaxies in all environments.

Keywords: galaxies: evolution – galaxies: structure –galaxies:stellar content – galaxies: fundamental parameters

INTRODUCTION

One approach to independently assess the evolutionary state of galaxies is to utilize classical scaling relations to establish connections between the shapes and physical sizes of the stellar distribution with the galaxy's luminosity (Kormendy 1977) and stellar masses (Shen et al. 2003). The size of a galaxy at a particular stellar mass, as well as the distribution of its stellar population, provide valuable insights into the galaxy's assembly history. Both these factors are indicative of how a galaxy has evolved. Distinct trends for spheroid and disk-like morphologies are observed in the stellar mass-size relation (MSR), as reported by Kauffmann et al. in 2003.

The correlation between the sizes and stellar masses of the two sets of galaxies is noticeable at low redshift. This connection has been observed to be present up to $z \sim 3$ (Mowla et al. 2019). If secular processes are responsible for the growth in galaxy size, then the required mechanisms for growth would vary depending on the mass of the galaxy. The expansion of the stellar distribution in the larger galaxies might be due to the effect of quasar feedback. As the quasar feedback removes a significant amount of cold gas from the central regions, it could lead to an increase in the size of these galaxies. This phenomenon would be most noticeable in the most massive galaxies. Less massive galaxies, as per Fan et al. 2008, would experience adiabatic expansion due to the loss of mass caused by supernova explosions and stellar winds. There is an alternative theory that is gaining popularity among authors. This theory suggests that the growth in size of large galaxies is due to major mergers, as proposed by Naab et al. in 2007, or repeated dry minor mergers, as suggested by Oser et al. in 2010.

It appears that recent observations support the idea that high-mass galaxies grow from the inside out. This means that the cores of these galaxies were already formed at high redshifts, and the evolution is observable in the outer parts of the galaxies. As a result, the size and stellar mass of these galaxies increase continuously over time. These findings have been reported in studies such as Pérez et al. (2013) and van Dokkum et al. (2010).

The evolution of galaxies in terms of their physical structure is influenced by the environment they are situated in. It is believed that galaxy evolution is accelerated in dense environments, leading to the production of more massive systems at a faster rate. This is according to Shankar's research in 2013. The expulsion of gas from the galaxy halo or disk, as well as the quick depletion of available fuel, are both caused by mechanisms such as galaxy harassment, strangulation, suppressed accretion, and ram pressure. These mechanisms essentially eliminate the fuel reserves required for the formation of new stars. The intracluster medium captures the gas as it is stripped away, while the stars within the galaxy's disk undergo aging, causing the disk to fade and redden. Galaxies that are actively forming stars and move into a densely populated area, like a cluster, are anticipated to be stopped from forming stars quite effectively within the first 1-3 billion years (at most 6 billion years) of their arrival, regardless of their initial stellar mass (Oman & Hudson 2016).

We suggest examining the stellar mass-size relation of galaxies in various environments to gain a deeper understanding of their global evolution. In Sect. 2, the sample selection and data analysis are described. The discussion of the results is provided in Sect.

DATA AND SAMPLE SELECTION

To compare galaxy properties in various environments, we use simulated galaxies from the Millennium cosmological simulation (Springel et al., 2005). We choose our simulated galaxies from catalogues (MRscPlanck1) of galaxy merger trees generated by applying the semi-analytic code L-Galaxies, as outlined in Ayromlou et al. 2021, to subhalo merger trees adjusted to conform to the Planck cosmology with $\Omega_\Lambda = 0.685$, $\Omega_m = 0.315$, $n_s = 0.961$, $\sigma_8 = 0.826$, m_p (M_{sun}/h) = 9.61104 x 10^8, L (Mpc/h) = 480.279 and h = 0.673($\mathrm{kms^{-1}\,Mpc^{-1}}$) for comparison with other studies analyzing the relation between stellar mass and size. The L-Galaxies model comes equipped with a comprehensive chemical enrichment scheme developed by Yates et al. in 2013. Additionally, it includes galaxy stellar and gas discs that are resolved radially, as described in Fu et al.'s work from 2013. The database for this model also encompasses the Local Background Environment properties of subhaloes, which were outlined by Ayromlou et al. in 2019.

We selected all simulated galaxies brighter than ~ -18 in the r-band filter and lie in the z $\sim$ 0 (snapshot 57). These leaves ~940,000 galaxies in our final simulated sample. In the Millennium Simulation, the Friends-of-Friends (FOF) algorithm is employed to recognize and differentiate dense environments, such as galaxy clusters and groups. (Davis et al. 1985, Ayromlou et al. 2021).

Having recognized 696404 galaxies in dense cosmic structures via the FOF algorithm, we established a criterion to distinguish between groups and clusters. For defining groups, we consider a range of 8 to 15 members, whereas for clusters, we have chosen those that contain more than 100 members. From the initial data, we have identified ~ 30000 galaxies in 171 clusters and ~ 40000 galaxies in 3775 group in these dense environments.

Furthermore, we aimed to compare the stellar mass-size relation of galaxies in dense and under-dense environments. Consequently, galaxies located in under-density environments (voids) were identified from the initial data. To accomplish this, we utilized the void finder algorithm initially presented by Aikio & Mähönen (1998; hereafter referred to as the AM algorithm). This algorithm has been upgraded to its 3D version by Tavasoli et al. (2013). Finally, the total count of galaxies found in the voids was $\sim$40000.

We have undertaken a comprehensive study to examine the impact of the environment on the size, stellar mass, and star formation rate of galaxies. We have categorized the galaxies by their morphological traits in every environment to achieve our objective. For this purpose, we have specifically chosen elliptical galaxies with a bulge-to-total ratio $(B/T) \geq 0.7$ and spiral galaxies with a $(B/T) \leq 0.4$. Table 1 exhibits the final dataset for each environment, categorized by the morphology of the galaxies. The initial dataset underwent the application of the specified conditions to arrive at this result.

Table 1. The final sample includes the count of galaxies in three galactic environments distinguished by galaxy morphology.

	Voids	Groups	Cluster
Spirals	34335	23730	19461
Ellipticals	2023	6258	3070

RESULTS

Mass-size relation of galaxies

In Figure 1, we have illustrated the simulation outcomes for Z = 0, in the form of median mass-size relations based on a three-dimensional stellar Half Mass Radius. Each of the two panels concentrates on scrutinizing the median mass-size relation in three varied environments, void, group, and cluster, shown in blue, red, and green respectively, in the mass ranges of 8 < log (M/M_{sun}) < 12.5.

The graph on the left clearly shows that in all mass ranges more massive spiral galaxies are larger than less massive spiral galaxies, regardless of their environment. In the other graph, there is an increasing trend in the size of all types of elliptical galaxies with the increase of the mass, although the size experiences a small decrease in masses ranging from 8.0 to 9.5 bins. The findings we have obtained are consistent with the outcomes presented in Shen's (2003) and A. van der Wel's (2014) studies. The researchers conducted their studies using the mass ranges of [9,12] in the Sloan Digital Sky Survey (SDSS) and CANDELS/3D-HST correspondingly. It has been observed that elliptical

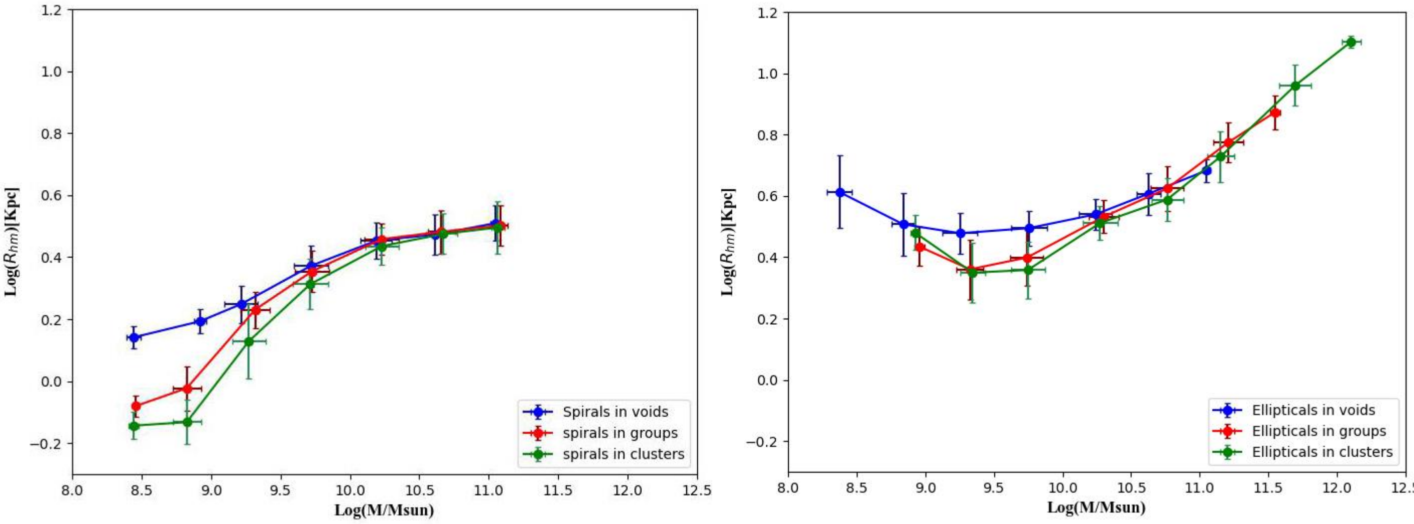

Figure 1. Comparison of Median mass- size relation of galaxies in Millennium simulation ($z = 0$) in different environments based on three-dimensional half- mass sizes. Overall, galaxies sizes increase as their masses grow. Furthermore, low-mass galaxies are affected by environments while high-mass galaxies are independent of environments.

galaxies are larger than spiral galaxies at the same mass, regardless of environment. This difference is particularly noticeable in voids, where the size difference between ellipticals and spirals is more pronounced. A closer look at spiral galaxies shows that low-mass ([8,10]) galaxies are more affected by the environment than high-mass galaxies. Additionally, spiral galaxies within voids are generally larger than those within groups and clusters. The same results were reported by Cebrian (2014). We observe that the relation between the size and stellar mass of high-mass spiral galaxies is independent of their environment.

On the other hand, elliptical galaxies with masses ranging between 9 and 10.5 are more impacted by the environment than high-mass galaxies. In this mass range, elliptical galaxies' sizes are moderately larger in voids than in groups and clusters. When masses exceed 10.5, the environment does not influence the mass-size relation of elliptical galaxies.

Elliptical galaxies whose masses range between 8 and about 9.5 experience a slightly negative slope; the same trend was reported by Genel (2021) in the IllustrisTNG simulation for quenched/early-type galaxies. We analyzed their populations morphologically, and a mean B/T value of around 0.95 was calculated. It can be inferred from the data that galaxies falling under the mentioned mass ranges tend to be more spherical in shape. We propose that the galaxies in question may be categorized as compact spheroidal galaxies.

Specific Star Formation Rate-Stellar Mass Relation of Galaxies

To explore the impact of the environment on galaxy properties, particularly focusing on the specific star

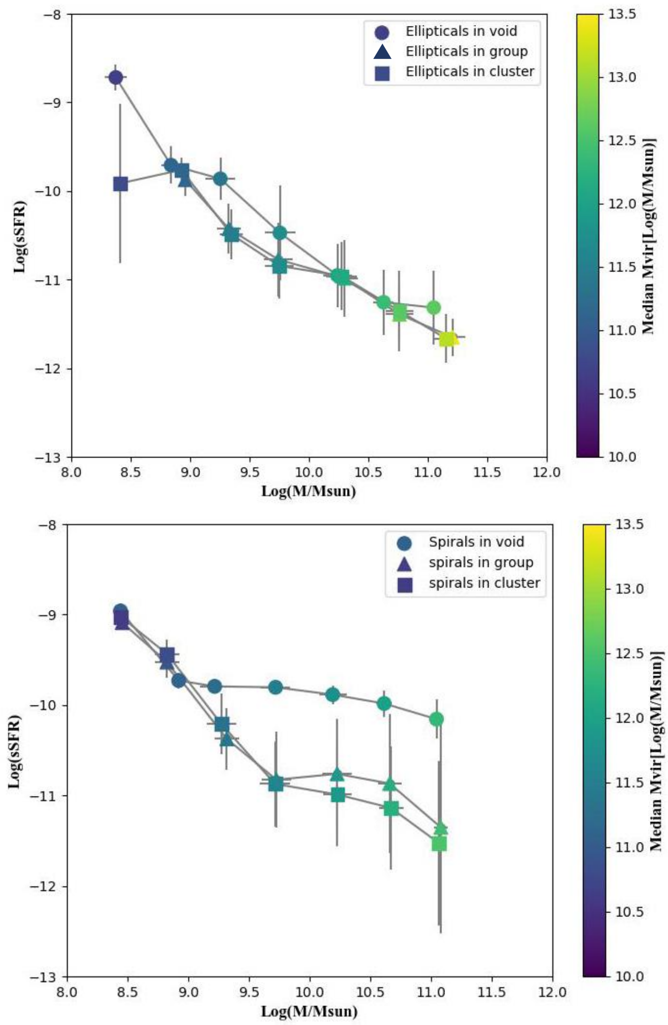

Figure 2. Comparison of Median Ssfr- Median stellar mass of galaxies in different environments. First panel describe for spirals and second shows pattern for ellipticals. The Mvir (total mass of halo in viral radius) is not influence on Ssfr for both populations.

formation rate (sSFR), the median of sSFR is calculated based on the median stellar mass of galaxies in different ranges for both spiral and elliptical populations. We also studied two critical factors affecting star formation rate in different environments, which are the total halo mass (M200/Msun) [1], and the Mass in the cold (star-forming) gas disc(McoldGas/Mstar) inside galaxies. We will represent these masses using a color bar that shows the median values of each type.

In Fig.2, we have separated our sample into spirals and ellipticals and plot median sSFR as a function of median stellar mass for each mass bin in different environments, and objects are color-coded according to their total median of halo mass. The two panels depict that the increase in stellar mass is accompanied by a clear decrease in the specific star formation rate (sSFR). The first panel illustrates that the specific star formation of elliptical galaxies is not significantly influenced by their environments. The second panel also indicates that the specific star formation rate (sSFR) of high-mass spiral galaxies is larger in voids as compared to galaxies in groups and clusters within the same mass range as reported by Kennicutt (1983).

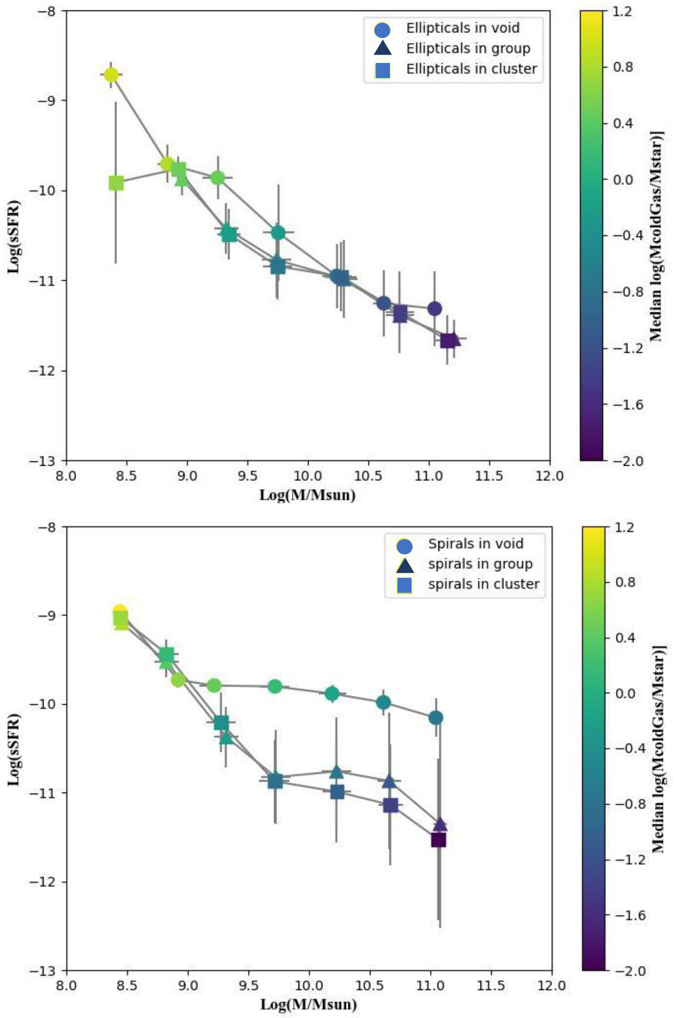

Figure 3. Comparison of Median sSFR - Median stellar mass of galaxies in different environments. Thes higher star formation rate in galaxies located in voids can be attributed to the greater amount of cold (star-forming) gas present in these galaxies.

The study demonstrates that the properties of environments influence the star formation rate of spiral galaxies. Upon scrutinizing the diagram closely, it becomes apparent that the variation in sSRF among galaxies in distinct environments cannot be attributed to the difference in their total halo mass.

In Fig. 3, we have generated two new plots that display the median sSFR of galaxies based on their median stellar mass of galaxies. However, this time we have used the mass in the cold (star-forming) gas disc as color-coded according to their median mass of cold Gas of galaxies in each mass bin for our two populations of galaxies in voids, groups, and clusters. Galaxies in voids, particularly spirals, possess a greater amount of cold gas mass compared to their counterparts in other environments. This leads to an increased rate of star formation in these galaxies. Therefore, the amount of cold gas mass plays a crucial role in sSFR in galaxies residing in diverse environments.

DISCUSSION

Throughout this paper, to demonstrate the possible effect of environments on the stellar mass-size relation and specific star formation rate (sSFR) of galaxies, we divided our Millennium's data into dense (groups and clusters) and under-dense (voids) environments. Two different types of interactions could explain our findings: hydrodynamic interactions and gravitational interactions.

We have analyzed the relation between galaxies' size and mass in low- and high-density environments. Our findings indicate that spirals with low stellar mass that exist within voids tend to be larger when compared to their counterparts in groups and clusters. In addition, we demonstrate that spirals with high stellar mass exhibit low sSFR when found in dense environments. We analyze how the halo mass and the mass of cold gas in these galaxies impact their behavior. Our findings indicate that the mass of cold gas plays a significant role in this behavior. There exist several mechanisms in dense environments that can suppress star formation by eliminating or disrupting the interstellar gas in galactic disks and halos.

Due to their shallow gravitational potential, low-mass spirals are especially susceptible to environmental interactions. Gravitational interactions in clusters, most probably in the form of harassment, can efficiently remove stars and gas from the outer parts of spiral galaxies and even transform the galaxies' morphology. (Barway et al.2009; Boselli and Gavazzi 2006). The smaller size of low-mass spirals in dense environments could be explained as we have discussed.

1. For every FOF halo, there is a virial radius, R_{200}, defined as the radius in which the matter density is 200 times the critical density of the Universe. The mass within R_{200} is known as the virial mass, M_{200}.

In comparison to voids, there is evidence that the star formation rate of a massive spiral galaxy has to be balanced by the accretion of cold gas (Sancisi et al. 2008) and hot gas (Rasmussen et al 2009). Star formation consumes the interstellar medium in a matter of a few Gyr when the gas halo is absent (Larson et al. 1980). The extended diffuse gas halo of galaxies can be stripped by ram pressure and tidal interaction in dense environments, the concept of starvation and strangulation (Bekki et al. 2002). This can decrease the star formation rate and cause high-mass galaxies to turn red (Kapferer et al 2008).

We found that the size and the sSFR of elliptical galaxies are slightly larger in voids compared to dense environments within certain ranges. This could be attributed to the lower density of galaxies and intergalactic medium in void regions, allowing for gas accretion and star formation process (H. Lietzen 2012). Further studies with a larger amount of data will shed light on the subject matter.

CONCLUSION

Our comprehensive analysis of data from the Millennium simulation has provided valuable insights, summarized as follows:

- Our studies on low-mass spiral galaxies have yielded significant findings on the impact of their environment on size. In denser environments, gravitational interaction and harassment cause a decrease in disc size. Conversely, high-mass spiral galaxies in under-density environments experience a lack of these interactions, resulting in a larger disk size.

- Our research indicates that the specific star formation rate of low-mass spiral galaxies is closely tied to the abundance of cold interstellar gas, which drives their rate of star formation. Interestingly, we observed that this abundance remains consistent across all three environments we studied. We hypothesize that this may be due to the weaker gravitational potential resulting in a lack of halo gas, rendering environmental factors such as ram pressure ineffective in their star formation rate.

-Our research indicates that gravitational interactions do not affect the size of high-mass spiral galaxies. This finding implies that the evolutionary process of these galaxies is uniform in all three environments. The effect of environments on sSFR is significant. Galaxies in denser environments experience the removal of halo gas due to gravitational interactions and ram pressure stripping, which can lead to a decrease in the amount of cold gas. As a result of the decline in the cold gas abundance, the star formation rate drops. Galaxies in voids are completely isolated and can retain their cold gas, which in turn allows them to continue star-forming. It should be noted that despite the mass of high-mass spirals, their halo mass remains consistent across all ranges and does not impact their ability to form stars.

- We have found that the environment does not affect the size and star formation rate of high-mass elliptical galaxies. Elliptical galaxies with low mass tend to be slightly larger when found in less dense environments, and they also exhibit a higher star formation rate compared to those found in denser environments. Further investigation using a larger dataset is necessary to explore.

-We have found a population of elliptical galaxies in voids that exhibit high star formation rates (sSFR) and a higher bulge-to-total (B/T) ratio. These galaxies could potentially be star-forming spheroidal galaxies. These galaxies may have undergone a recent period of star formation due to minor mergers or being in gas-rich environments. However, further research is necessary to better understand this particular population.

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