Do galactic bars depend on environment?: An information theoretic analysis of Galaxy Zoo 2

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ABSTRACT

We use an information theoretic framework to analyze data from the Galaxy Zoo 2 project and study if there are any statistically significant correlations between the presence of bars in spiral galaxies and their environment. We measure the mutual information between the barredness of galaxies and their environments in a volume limited sample ($M_r \leq -21$) and compare it with the same in datasets where (i) the bar/unbar classifications are randomized and (ii) the spatial distribution of galaxies are shuffled on different length scales. We assess the statistical significance of the differences in the mutual information using a t-test and find that both randomization of morphological classifications and shuffling of spatial distribution do not alter the mutual information in a statistically significant way. The non-zero mutual information between barredness and environment arises due to the finite and discrete nature of the dataset which can be entirely explained by mock Poisson distributions. We also separately compare the cumulative distribution functions of the barred and unbarred galaxies as a function of their local density. Using a Kolmogorov-Smirnov test, we find that the null hypothesis can not be rejected even at 75\% confidence level. Our analysis indicates that environments do not play a significant role in the formation of a bar, which is largely determined by the internal processes of the host galaxy.

Key words: methods: statistical - data analysis - galaxies: formation - evolution - cosmology: large scale structure of the Universe.

1 INTRODUCTION

Observations suggest that a significant fraction of spiral galaxies in the present universe are barred (Eskridge et al. 2000; Marinova & Jogee 2007; Barazza, Jogee, & Marinova 2008). Even our Milky Way is known to host a bar-like structure (Binney et al. 1991; Wegg, Gerhard, & Portail 2015). Bars are extended linear structures that results from disc instabilities (Toomre 1964). The stellar bars transfer angular momentum to the outer disc (Lynden-Bell 1979; Athanassoula 2002; Berentzen et al. 2007) and also help to redistribute angular momentum between the disk and the surrounding dark matter halo (Weinberg 1985; Debattista & Sellwood 2000; Athanassoula 2003; Berentzen, Shlosman, & Jogee 2006). They are efficient in driving gas into the central regions of galaxies which can trigger starbursts and AGN activity and also help to grow a central bulge component (Schwarz 1981; Kormendy 1982; Shlosman, Frank, & Begelman 1989; Hunt & Malkan 1999; Knapen et al. 1995; Knapen, Shlosman, & Peletier 2000; Kormendy & Kennicutt 2004; Jogee, Scoville, & Kenney 2005; Laurikainen, Salo, & Buta 2004; Sheth et al. 2005; Laurikainen et al. 2007). The bars can thus play a driving role in the evolution of disk galaxies.

It is still not clear if the formation and evolution of bars are purely governed by internal secular processes. Galaxies form and evolve in diverse environments in the cosmic web. They form at the centre of the dark matter halos (White & Rees 1978) which are embedded in different environments of the cosmic web. The mass, shape and angular momentum of the dark matter halos are known to be influenced by their large-scale environments (Hahn et al. 2007,b). So the environment may impart an indirect influence on the formation and evolution of galactic bars. The different assembly history of the dark matter halos causes the early-forming low mass halos to cluster more strongly as compared to the late-forming halos of similar mass (Croton, Gao & White 2007; Gao & White 2007). Such clustering bias of dark matter halos may indirectly affect the formation of galactic bars. The direct external influence of environments may also play a role in the formation and evolution of bars in spiral galaxies. Studies with N-body simulations suggest that tidal interactions and the passage of a companion galaxy can trigger the formation of bars in disk galaxies (Byrd & Valtonen 1990; Gerin, Combes, & Athanassoula 1990; Berentzen et al. 2004; Martinez-Valpuesta et al. 2017; Lokas 2018; Ghosh et al. 2020). These trends have been also supported by observa-
tions (Elmegreen, Elmegreen, & Bellin 1990; Giuricin et al. 1993; Méndez-Abreu et al. 2012).

It would be interesting to know whether the formation and evolution of galactic bars is influenced by their environment. A significant number of studies have been carried out to test the correlation between the environment and the presence of bars in spiral galaxies. Thompson (1981) studies the radial distribution of barred galaxies in the Coma cluster and find that a significantly larger fraction of barred galaxies is found at the cluster core. Giuricin et al. (1993) use NGC catalogue to study the effect of local galaxy density on the presence of bars and find that the early type and low luminosity spiral galaxies in high density environments tend to be barred. Eskridge et al. (2000) find a slightly higher fraction of barred galaxies in the Fornax and Virgo clusters compared to the fields. Barway, Wadadekar, & Kembhavi (2011) study bar fraction in lenticular galaxies using SDSS DR7 and find a higher fraction of barred galaxies in clusters than in the fields. Skibba et al. (2012) study the environmental dependence of bars in spiral galaxies using the Galaxy Zoo 2 project and find that the redder galaxies with higher stellar mass are more likely to have bars. They reported a significant bar-environment correlation which shows that the barred galaxies more frequently occur in denser environments than their unbarred counterparts.

Contrary to these findings, several studies reported no dependence of bars on the environment. van den Bergh (2002) investigate the dependence of bar frequency in fields, groups and cluster environments and find no evidence for any role of environment on the formation of bars. Li et al. (2009) studied the projected redshift-space two-point cross-correlation functions of barred and unbarred galaxies in the SDSS and find that at a fixed stellar mass, the clustering of barred and unbarred galaxies are indistinguishable over the scales 20 kpc - 30 Mpc. Barazza et al. (2009) find that the fraction and properties of bars in clusters and fields are quite similar. Aguerri, Méndez-Abreu, & Corsini (2009) study bar fraction as a function of local galaxy density using SDSS DR5 and find that there is no difference in the local galaxy density of barred and unbarred galaxies. Cameron et al. (2010) investigate the evolution of bar fraction in the COSMOS field and reported that the evolution of the barred galaxy populations does not depend on the large-scale environmental density. Méndez-Abreu, Sánchez-Janssen, & Aguerri (2010) use HST ACS data to study the bar fraction in the Coma cluster and find that the bar fraction does not vary significantly in the centre and outskirts of the cluster. Martínez & Muriel (2011) study the relationship between the fraction of barred spirals and a number of environmental parameters and find that the fraction of barred spirals is insensitive to their environment. Lee et al. (2012) use SDSS DR7 to study the dependence of bars on environment and find that the fraction of barred galaxies is independent of their large-scale environment when the other galaxy properties are fixed. Marinova et al. (2012) study bars in massive disk galaxies using data from the HST ACS Treasury survey of the Coma cluster and find that the bar fraction does not show a statistically significant variation across environments.

Clearly, the correlation between the occurrence of bars in spirals and their environment still remains a debated issue and there are no clear consensus on the bar-environment correlation.

Most of the studies in this field are plagued by smaller size of data samples which made it difficult to derive statistically meaningful conclusions. The SDSS (York, et al. 2000) is the largest and most successful redshift survey to date which has provided the most detailed three dimensional map of the nearby universe and a wealth of information about the individual galaxies. The Galaxy Zoo (Lintott et al. 2008, 2011) is a citizen science project based on the SDSS and HST data which invites volunteers to help in the morphological classification of a large number of galaxies by visual inspection of their images. We plan to use data from the Galaxy Zoo 2 project (Willett et al. 2013) for the present work.

Pandey & Sarkar (2017) proposed an information theoretic framework to study the correlation between the morphology of a galaxy and its large-scale environment. They considered spirals and ellipticals as two distinct morphological classes and find a synergic interaction between morphology and environment up to a length scale of 30 h⁻¹ Mpc. Recently Sarkar & Pandey (2020) show that the observed excess mutual information between morphology and environment are statistically significant at 99.9% confidence level. Another study by Bhattacharjee, Pandey, & Sarkar (2020) show that a conditioning on stellar mass does not explain the statistically significant mutual information between morphology and environment on larger length scales. Galactic bar is an important morphological feature based on which a spiral galaxy is further classified as barred or unbarred. It would be natural to ask if there exists a bar-environment correlation similar to the correlation observed between morphology and environment.

We would like to measure the mutual information between barredness of a galaxy and its environment on different length scales. One can randomize the information about barredness and also shuffle the spatial distribution after dividing it into smaller sub-cubes. Comparing the mutual information in these distributions with that from the original distribution would allow us to test the statistical significance of any observed correlation between barredness and environment (Sarkar & Pandey 2020). In this work, we use this information theoretic framework to test the large-scale environmental dependence of galactic bars if any.

The local density of galaxies governs the various external influences such as tidal interactions which may act as an external trigger for bar formation. Comparing the number density of galaxies at the locations of the barred and unbarred spirals can elucidate this issue. Keeping this in mind, we also separately test any effects of local density on the presence of galactic bars in spiral galaxies.

2 DATA

2.1 SDSS and Galaxy Zoo 2 data

We use data from the Sloan Digital Sky survey (SDSS) for the present analysis. We use Structured Query Language (SQL) to extract the required data from the SDSS SkyServer. The SDSS (York, et al. 2000) covers 9,376 square degrees of sky for spectroscopy where 2,863,635 galaxies were chosen as targets. The morphological information of galaxies in the SDSS main-sample (Abazajian et al. 2009) is provided by Galaxy Zoo 2 (GZ2) (Willett et al. 2013). GZ2 is the second phase of the original Galaxy zoo project(GZ1) (Lintott et al. 2008) which is a citizen scientist programme for morphological classification of galaxies through visual inspection of images. GZ1 provides morphological classifications of ~ 900000 galaxies drawn from the SDSS. GZ2 targets a subset of ~ 300000 galaxies from GZ1 for a more detailed morphological classifications. The GZ2 decision tree consists of a total of 11 tasks. It differentiates the galaxies having a disk from the smooth (E/S0) ones and also record the various prominent

1 https://skyserver.sdss.org/casjobs/
2 http://zoo1.galaxyzoo.org
features of the galaxies like presence of bars, number of spiral arms, arc or lens shapes. We combine the zoomMainSpecz table with specobjAll and photoz to retrieve the required information. We use a critical value of debiased vote fraction to select the spirals (ft04_spiral_dr8_spiral_debiased > 0.6). The barred and unbarred spirals are selected using a similar cut-off in the value of the debiased vote fraction (ft03_bar_dr6_bar_debiased > 0.6 and ft03_bar_dr07_no_bar_debiased > 0.6). The cut-off values for the debiased vote fractions were chosen so as to have a reasonable number of galaxies in the volume limited sample to be prepared. We identify a contiguous region in the northern galactic hemisphere and select all the classified barred and unbarred spirals between right ascension 135° and 255° and declination 0° and 60°. We prepare a volume limited sample by restricting the r-band Petrosian absolute magnitude to $M_r \leq -21$. The galactic extinction corrected r-band Petrosian apparent magnitude limit of the sample is $m_r < 17$. We get a volume limited sample which extends up to redshift $z \leq 0.087$ and contains a total 11260 galaxies (2214 barred and 9046 unbarred). We then extract all the galaxies within a cubic region of sides $132 h^{-1}$ Mpc from the volume limited sample. This is the largest cube that can fit within the volume limited sample. The resulting cube contains a total 3420 galaxies of which 690 are barred and 2730 are unbarred. We show the definition of the volume limited sample, the spatial distributions of the galaxies in the sample and the variations of comoving number density in it in Figure 1.

We use the ΛCDM cosmological model with $\Omega_{m0} = 0.315, \Omega_{b0} = 0.685$ and $h = 0.674$ (Planck Collaboration, et al. 2018) for conversion of redshifts to comoving distances.

### 2.2 Mock Poisson samples

We generate 10 mock Poisson samples each with 3420 points distributed within a cubic region of side $132 h^{-1}$ Mpc. We randomly label 690 points as barred and 2730 points as unbarred in each of these distributions. These mock data sets have the same number of galaxies as in the actual SDSS data cube. The ratio of barred to unbarred spirals are also kept same as the actual data.

### 3 METHOD OF ANALYSIS

We now have a magnitude limited sample of the spiral galaxies defined within a cubic region of side $L h^{-1}$ Mpc. We divide this cube in $N_d = n_d^3$ voxels with size $d = (\frac{1}{n_d}) h^{-1}$ Mpc. One can have different sets of voxels by changing the number of grids $n_d$. Different choices of $n_d$ allow us to study the environment on different length scales.

Let us now define a discrete random variable $X$ that represents the environment at a certain length scale. The probability of finding a randomly selected galaxy in the $i^{th}$ voxel will be $p(X_i) = \frac{N_i}{N}$, where $N_i$ is the number of galaxies in the $i^{th}$ voxel and $N = \sum_{i=1}^{N_d} N_i$ is the total number of galaxies in the entire cube. The random variable $X$ have $N_d$ outcomes ($X_i : i = 1, 2, ..., N_d$).

The information entropy (Shannon 1948) associated with the random variable $X$ on length scale of $d h^{-1}$ Mpc is given by,

$$H(X) = -\sum_{i=1}^{N_d} p(X_i) \log p(X_i)$$

$$= \log N - \sum_{i=1}^{N_d} \frac{N_i \log N_i}{N}. \quad (1)$$

Let us now define another variable $Y$ that represents the presence or absence of bar in spiral galaxies. Here, $Y$ only takes two values $Y_1$ for barred & $Y_2$ for unbarred. If there are $N_1$ barred and $N_2$ unbarred galaxies in the cube then the Shannon entropy associated with the variable $Y$ will be

$$H(Y) = -\left(\frac{N_1}{N} \log \frac{N_1}{N} + \frac{N_2}{N} \log \frac{N_2}{N}\right)$$

$$= \log N - \frac{N_1 \log N_1 + N_2 \log N_2}{N}. \quad (2)$$

Here, $N = N_1 + N_2$ is the total number of galaxies in the sample. Any variation in the voxel size will not change the number of barred and unbarred galaxies and the value of $H(Y)$ is independent of the grid size.

We also calculate the joint entropy for the variables $X$ and $Y$. Which is given by,

$$H(X, Y) = -\sum_{i=1}^{N_d} \sum_{j=1}^{N} p(X_i, Y_j) \log p(X_i, Y_j)$$

$$= \log N - \frac{1}{N} \sum_{i=1}^{N_d} \sum_{j=1}^{N} N_{ij} \log N_{ij}. \quad (3)$$

Here $N_{ij}$ is the number of galaxies that resides in the $i^{th}$ voxel and belongs to the $j^{th}$ morphology. So we have,

$$\sum_{i=1}^{N_d} \sum_{j=1}^{N} N_{ij} = N.$$

If the two variables $X$ and $Y$ are uncorrelated then $H(X) + H(Y) = H(X, Y)$. Otherwise the joint entropy would be smaller than the sum of the individual entropies, i.e. $H(X, Y) < H(X) + H(Y)$.

We calculate the mutual information between the two variables $X$ and $Y$ as,

$$I(X ; Y) = H(X) + H(Y) - H(X, Y). \quad (4)$$

The mutual information measures the amount of information shared between two random variables. In other words, it is the reduction in uncertainty in the outcome of one random variable due to the pre-existing knowledge of the other. Higher the mutual information, greater is the association between the two variables. The mutual information measures the association between two random variables irrespective of the nature of the random variables and their relationship.

#### 3.1 Randomizing the classification of barred and unbarred galaxies

We temporarily obliterate the actual bar/unbar classifications of the spiral galaxies in the cube and randomly tag each of them as barred or unbarred. We do this in such a way that the total number of
Figure 1. The top left panel shows the definition of the volume limited sample used in the present analysis. The projected distribution of the galaxies in the volume limited sample is shown in the top right panel. The galaxies within the cubic region are shown with a different colour in the same panel. The bottom left panel shows the comoving number density of galaxies as a function of distance along three different axes within the cubic region. The comoving number densities are obtained in uniform slices of thickness $10.15h^{-1}$ Mpc.

barred and unbarred galaxies in the resulting distribution remains the same as before. Such randomization of classifications would not change $H(X)$ or $H(Y)$ but the joint entropy $H(X, Y)$ of the resulting distribution is expected to change when the variables are correlated. The randomization procedure destroys any existing correlations between $X$ and $Y$ turning them into independent random variables. So any mutual information of physical origin should ideally diminish to zero after the randomization. We generate 10 randomized datasets from the actual data for our analysis.

3.2 Shuffling the spatial distribution

The SDSS data cube of sides $L = 132h^{-1}$ Mpc is divided into $N_c = n_s^3$ sub cubes of size $l_s = \frac{L}{n_s}$, where $n_s$ is the number of segments on each side. We shuffle (Bhavsar & Ling 1988) the sub-cubes to obtain a new distribution which contains same number of galaxies distributed within the same volume. This will destroy any existing correlations between the environment and the barredness beyond the size of the sub-cubes used for shuffling. A detail description of the shuffling procedure can be found in Sarkar & Pandey (2020). The sub cubes are randomly interchanged with random rotations in multiples of $90^\circ$ along any of the three axes. We repeated this process for $100 \times N_c$ times so as to allow each of the sub-cubes to swap its position multiple times, with other sub-cubes. The shuffling exercise is performed for three different sizes of shuffling unit, $n_s = 3$, $n_s = 7$ and $n_s = 11$ which corresponds to $l_s = 44h^{-1}$ Mpc, $l_s = 19h^{-1}$ Mpc and $l_s = 12h^{-1}$ Mpc respectively. In order to avoid any spurious correlations, we chose the size of the
shuffling units to be different from the grid sizes used for the estimation of mutual information. We also ensure that the size of the shuffling units are not integral multiple of grid sizes and vice versa. We generate 10 shuffled realizations from the original SDSS data for the present analysis.

3.3 Testing statistical significance of mutual information with t-test

An equal variance t-test is used to estimate the statistical significance of the mutual information between environment and barredness of the spiral galaxies in the actual SDSS data. At each length scale, we compare the mutual information obtained for randomized or shuffled data with that from the original SDSS data. The t-score at each length scale is given by,

\[
t = \frac{\mu_1 - \mu_2}{\sigma_1 + \sigma_2} \frac{1}{\sqrt{n_1 + n_2}}
\]  

(5)

Here \(\mu_1\) and \(\mu_2\) are the mean values and \(\sigma_1\) and \(\sigma_2\) are the standard deviations at a given length scale for the two data sets under consideration. \(\sigma_1 = \frac{\sqrt{(n_1-1)\sigma_1^2 + (n_2-1)\sigma_2^2}}{n_1 + n_2 - 2}\), where \(n_1\) and \(n_2\) are the number of samples used to estimate mean and standard deviation of the two data sets. \((n_1 + n_2 - 2)\) is the degree of freedom associated with the test.

3.4 Local density of barred and unbarred spirals

We find the distance to the \(k^{th}\) nearest neighbour for each galaxies in the cube and estimate the local number density of galaxies around it. The \(k^{th}\) nearest neighbour density (Casertano & Hut 1985) around a galaxy is defined as

\[
\eta_k = \frac{k - 1}{V(r_k)}
\]  

(6)

Here \(r_k\) is the distance to the \(k^{th}\) nearest neighbour and \(V(r_k) = \frac{4}{3}\pi r_k^3\) is the volume of the sphere having a radius \(r_k\). In this work, we have used \(k = 4\). The value of \(r_k\) could be overestimated for the galaxies near the boundary of the cube. Consequently, the local density of the galaxies near the boundary could be underestimated. We calculate the local density for only those galaxies which have \(r_k < r_b\), where \(r_b\) is the closest distance of the galaxy from the boundary wall. After using this criteria we are left with \(N'_1 = 514\) barred galaxies and \(N'_2 = 2002\) unbarred galaxies. We estimate the densities at the locations of the barred and unbarred galaxies using Equation 6. The local density is estimated in units of \(h^3\) Mpc\(^{-3}\).

3.5 Testing the difference in the local density of barred and unbarred spirals with Kolmogorov-Smirnov test

We use the two-sample Kolmogorov-Smirnov test to compare the cumulative distributions of density for the barred and unbarred spirals. The Kolmogorov-Smirnov test is a non-parametric test which makes no assumption about the distributions. The null hypothesis assumes that both barred and unbarred galaxies are sampled from populations with identical distributions. We calculate the maximum difference between the two cumulative distributions. The supremum difference between the two cumulative distribution functions \(D_{KS}\) is defined as

\[
D_{KS} = \sup_{\eta_k} \{|f_{1,m}(\eta_k)-f_{2,m}(\eta_k)|\}
\]  

(7)

\(f_{1,m}(\eta_k)\) and \(f_{2,m}(\eta_k)\) are the cumulative distribution functions for barred and unbarred spirals at the \(m^{th}\) bin where \(m \in \{1,2,3,...,N'\}\). \(\sup\) is the operator that finds the supremum of all the \((N'_1 + N'_2)\) differences. Here \(\sum_{m=1}^{N'} f_{1,m}(\eta_k) = \sum_{m=1}^{N'} f_{2,m}(\eta_k) = 1\).

The critical value of \(D_{KS}\) for a given significance level \((\alpha)\) is given by,

\[
D_{KS}(\alpha) = \sqrt{-\ln(\frac{\alpha}{2})} \frac{N'_1 + N'_2}{2N'_1N'_2}
\]  

(8)

where \(N'_1\) and \(N'_2\) are the number of barred and unbarred spirals in the sample. If \(D_{KS} > D_{KS}(\alpha)\) then the null hypothesis can be rejected at level \(\alpha\). We test the null hypothesis at different significance level to find if the distributions of barred and unbarred spirals are same or different.

4 RESULTS

4.1 Effects of large-scale environments on galactic bars

We compare the mutual information in the randomized and shuffled data sets to that with the original SDSS data in Figure 2. The mutual information between barredness and environment in the SDSS data is shown in the top left panel of Figure 2. We find a non-zero mutual information between the barredness and the environment in the SDSS data, which decreases with increasing length scales. We would like to test the statistical significance of these non-zero mutual information. When we compare the mutual information in the original data with the randomized data sets, we find that the randomization of barred/unbarred classifications have no impact on the mutual information between barredness and environment. We also compare our results to mock Poisson distributions to understand the relevance of the observed non-zero mutual information. We find that the observed mutual information in the SDSS and Poisson data sets are nearly identical beyond 15 \(h^{-1}\) Mpc. The mock Poisson samples show a relatively higher mutual information than the original and randomized data at length scales below 15 \(h^{-1}\) Mpc. This may purely arise due to the dominance of Poisson noise on smaller length scales. This suggests that the observed non-zero mutual information originate from the finite and discrete character of the distributions. We use an equal variance Student’s t-test to identify any statistically significant differences between the original and randomized data sets. The t-scores at different length scales together with the critical value of t-score at 99.9% confidence level are shown in the top right panel of Figure 2. We tabulate the t-score and the associated p-value at each length scale in Table 1. The results show that the null hypothesis can not be rejected at this confidence interval. This analysis suggests that the large-scale environment of galaxies have no influence on galactic bars.

We then compare the mutual information in the original and shuffled data sets in the bottom left panel of Figure 2. The plot shows that shuffling the spatial distribution of galaxies with three different shuffling lengths have little to no influence on the mutual information. The process of shuffling the data is expected to destroy the mutual information at all length scales beyond the shuffling length. However, we do not observe any such decrease of mutual information when the data is shuffled on different length scales. We notice an increase in the mutual information in shuffled data sets at the smallest length scales. This is contrary to what one would expect in a shuffled distribution. When we compare our

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Figure 2. The top left panel shows the mutual information between barredness and environment as a function of length scales in the original SDSS data cube, mock Poisson data cubes and SDSS data cubes with randomized bar/unbar classification. The $1 - \sigma$ errorbars for the SDSS (randomized) and Poisson random datasets are obtained using 10 different realizations for each. We estimate the $1 - \sigma$ errorbars for the original SDSS data using 10 jack-knife samples drawn from the original dataset. The top right panel shows the $t$ score between original and randomized SDSS data at different length scales. The bottom left and bottom right panels of this figure show the same but for the shuffled SDSS data along with original SDSS data and mock Poisson datasets. The spatial distribution of galaxies within the SDSS data cube is shuffled with three different shuffling lengths and the corresponding results are shown together in the bottom left and bottom right panel of this figure. In each case, we ensure that the size of the sub-cubes used for shuffling the data, is not equal or integral multiple of the grid sizes used for calculating the mutual information.

Figure 3. This shows the cumulative distribution function of barred and unbarred spirals as a function of local galaxy density.
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Table 1. This table shows the $t$ scores between actual SDSS data and SDSS data with randomized bar/unbar classifications, at different length scales. The $p$ values associated with the $t$ scores are also listed in the same table.

| Grid size ($h^{-1}$ Mpc) | $t$ score | $p$ value |
|--------------------------|-----------|-----------|
| 11.00                    | 1.551     | $6.91 	imes 10^{-2}$ |
| 12.00                    | 1.292     | $1.06 	imes 10^{-1}$ |
| 13.20                    | 2.366     | $1.47 	imes 10^{-2}$ |
| 14.67                    | 2.182     | $2.13 	imes 10^{-2}$ |
| 16.50                    | 1.819     | $4.28 	imes 10^{-2}$ |
| 18.86                    | 3.912     | $5.11 	imes 10^{-4}$ |
| 22.00                    | 1.086     | $1.46 	imes 10^{-1}$ |
| 26.40                    | 2.255     | $1.84 	imes 10^{-2}$ |
| 33.00                    | 1.547     | $6.96 	imes 10^{-2}$ |
| 44.00                    | 0.788     | $2.20 	imes 10^{-1}$ |
| 66.00                    | 2.700     | $7.32 	imes 10^{-3}$ |

Table 2. This table shows the $t$ scores between original SDSS data and shuffled versions of the SDSS data, at different length scales. Three different shuffling length scales were used in the analysis. We ensure that for each $n_s$, the size of the sub-cubes employed for shuffling the data is not equal or integral multiple of the grid size used for the estimation of mutual information. The $p$ values associated with the $t$ scores are also tabulated here.

| Grid size ($h^{-1}$ Mpc) | $n_s = 3$ | $n_s = 7$ | $n_s = 11$ |
|--------------------------|-----------|-----------|-----------|
| $t$ score | $p$ value | $t$ score | $p$ value | $t$ score | $p$ value |
| 11.00 | - | - | 11.785 | $3.37 	imes 10^{-10}$ | 17.841 | $3.42 	imes 10^{-11}$ |
| 12.00 | 0.314 | $3.79 	imes 10^{-1}$ | 4.775 | $7.56 	imes 10^{-5}$ | - | - |
| 13.20 | 2.341 | $1.55 	imes 10^{-2}$ | 5.783 | $8.82 	imes 10^{-6}$ | 9.027 | $2.10 	imes 10^{-4}$ |
| 14.67 | - | - | 3.281 | $2.08 	imes 10^{-3}$ | 2.590 | $9.24 	imes 10^{-3}$ |
| 16.50 | 0.721 | $2.40 	imes 10^{-1}$ | 1.452 | $8.19 	imes 10^{-2}$ | 0.903 | $1.89 	imes 10^{-1}$ |
| 18.86 | 0.029 | $4.89 	imes 10^{-1}$ | - | - | 1.239 | $1.16 	imes 10^{-1}$ |
| 22.00 | - | - | 2.792 | $6.02 	imes 10^{-3}$ | 2.295 | $1.70 	imes 10^{-2}$ |
| 26.40 | 0.056 | $4.78 	imes 10^{-1}$ | 0.524 | $3.03 	imes 10^{-1}$ | 0.154 | $4.40 	imes 10^{-1}$ |
| 33.00 | 0.104 | $4.59 	imes 10^{-1}$ | 0.095 | $4.63 	imes 10^{-1}$ | 0.254 | $4.01 	imes 10^{-1}$ |
| 44.00 | - | - | 0.424 | $3.38 	imes 10^{-1}$ | 0.787 | $2.21 	imes 10^{-1}$ |
| 66.00 | 2.250 | $1.86 	imes 10^{-2}$ | 1.336 | $9.91 	imes 10^{-2}$ | 2.539 | $1.03 	imes 10^{-2}$ |

Table 3. This table lists the critical values $D_{KS}(z)$ for different significance level $z$ in the Kolmogorov-Smirnov test

| Significance level $z$ | 0.005 | 0.01 | 0.05 | 0.1 | 0.25 |
|------------------------|-------|------|------|-----|-----|
| Confidence level       | 99.5% | 99%  | 95%  | 90% | 75% |
| $D_{KS}(z)$            | 0.085584 | 0.080481 | 0.067154 | 0.060517 | 0.050420 |

results with that from mock Poisson distribution, it shows that an even higher mutual information is observed in the Poisson distributions at the smallest length scale. Shuffling the data randomizes the spatial distribution of galaxies and enhances the Poisson character of the distribution. It may be noted that the mean-intergalactic separation of our sample is $\sim 9 h^{-1}$ Mpc and the measurements of mutual information near these length scales would be dominated by Poisson noise. Evidently, we do not assign any physical significance to the increase in mutual information in the shuffled data at smallest length scales. The $t$-scores at different length scales in the shuffled data sets are shown in the bottom right panel of Figure 2. The critical $t$-score at 99.9% confidence level is also shown together in the same panel. The $t$-score and the associated $p$-value at each length scale for each shuffling length are tabulated in Table 2. The results clearly show that the null hypothesis cannot be rejected at 99.9% confidence level. Shuffling the spatial distribution on different length scales do not alter the mutual information between the barredness and the environment in a statistically significant way. This again suggests that the large-scale environment do not play a significant role on the formation of a bar in spiral galaxy.

4.2 Effects of small-scale environments on galactic bars

We also test if the local density of barred and unbarred galaxies are different in a statistically significant way. We estimate the local densities at the locations of barred and unbarred spiral galaxies. We compare their cumulative distribution functions as a function of separation of our sample is $\sim 1$–9 (2020).
length scales. So the small-scale environment cannot be held accountable for presence or absence of galactic bars in spiral galaxies.

5 CONCLUSIONS

Understanding the role of bars in spiral galaxies are central to understanding their formation. Bars are known to be the most efficient means to redistribute materials inside a galaxy. It is yet not clearly known why some spiral galaxies host a bar while others do not. The detail process of bar formation may be governed by several factors. Both the internal secular processes and external triggers may induce the bar formation in a galaxy. Besides, the large-scale environment and the assembly history of dark matter halos may also have an influence on the formation of galactic bars. All these possibilities must be tested against observations to identify the most influential factors governing the formation of galactic bars.

We have calculated the mutual information between the barredness of a galaxy and its environment on different length scales using the SDSS and Galaxy Zoo 2 data. We randomize the bar/unbar classification of galaxies and measure the mutual information between the barredness and environment. There are no statistically significant change in the mutual information between barredness and environment after the classifications are randomized. We also shuffle the spatial distribution of SDSS galaxies after dividing it in smaller sub-cubes and randomly interchanging their spatial locations along with random rotations. We also do not observe any statistically significant difference in the mutual information between the barredness and the environment after the data is shuffled on different length scales. The analysis do not provide any strong evidence against the null hypothesis which suggests that the large-scale environment of barred and unbarred galaxies are similar and there are no correlations between the barredness of a galaxy and its large-scale environment.

We also separately test any possible influence of local density on the presence of galactic bars. We measure the local density at the locations of barred and unbarred galaxies and then compare their cumulative distribution functions using a Kolmogorov-Smirnov test. The test favours the null hypothesis which indicates that the local density of barred and unbarred galaxies are quite similar. A study of the bar fraction in nearby galaxy clusters suggests that the bar formation in low-mass galaxies are expected to be more susceptible to their environment than the bright or massive galaxies (Méndez-Abreu et al. 2012). The volume limited sample analyzed in this work consists of brighter galaxies for which the bar formation may be unaffected by their environment.

In the present work, we explore any possible role of the small-scale and large-scale environments of galaxies on the formation of galactic bars. Our analysis clearly indicates that the presence or absence of bars in spiral galaxies do not depend on either their small-scale or large-scale environments. This suggests that the formation of galactic bar is largely decided by the internal processes of the host galaxy.

6 DATA AVAILABILITY

The data underlying this article is available in https://skyserver.sdss.org/casjobs/. The datasets were derived from sources in the public domain: https://www.sdss.org/ and http://zooll.galaxyzoo.org.

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