Exploring galaxy colour in different environments of the cosmic web with SDSS

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21 February 2020

ABSTRACT

We analyze a set of volume limited samples from the SDSS to study the dependence of galaxy colour on different environments of the cosmic web. We measure the local dimension of the galaxies to determine their embedding environments and find that the filaments host a higher fraction of red galaxies than the sheets at each luminosity. At a fixed luminosity, the fraction of red galaxies in filaments and sheets increases with the size of these structures. This suggests that the bigger structures have a larger baryon reservoir favouring higher accretion rate and larger stellar mass. At a fixed length scale, the fraction of red galaxies monotonically increases in all the environments with increasing luminosity. We also find that the average colour of the red and blue populations are systematically higher in the environments with smaller local dimension and increases monotonically in all the environments with luminosity. We observe that the bimodal nature of the galaxy colour distribution persists in all environments and all luminosities suggesting that the transformation from blue to red galaxy can occur in all environments.

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

1 INTRODUCTION

Understanding the formation and evolution of galaxies in the Universe is one of the most challenging problems in Cosmology. The modern galaxy surveys (2dFGRS, Colless et al. 2001; SDSS, York et al. 2000) reveal that the galaxies are distributed in the cosmic web (Bond et al. 1996) which is an interconnected weblike network comprising of different types of environments such as filaments, sheets, knots and voids. The galaxies come in various shape and size with different mass, luminosity, colour, star formation rate, metallicity and HI content. The galaxy properties vary across the different environments in the cosmic web. For example, the well known density-morphology relation suggests that the ellipticals are preferably found inside the dense groups and clusters whereas the spirals are intermittently distributed in the fields (Hubble 1936; Zwicky 1968; Oemler 1974; Dressler 1980; Goto et al. 2003). These findings are further supported by other studies with two-point correlation function (Willmer, da Costa, & Pellegrini 1998; Brown, Webstar, & Boyle 2000; Zehavi et al. 2003). These findings are further supported by other studies with two-point correlation function (Willmer, da Costa, & Pellegrini 1998; Brown, Webstar, & Boyle 2000; Zehavi et al. 2003). genus statistics (Hoyle et al. 2002; Park et al. 2005) and filamentarity (Pandey & Bharadwaj 2005, 2006) of the galaxy distribution. It is now well known that many other galaxy properties are strongly sensitive to their environment (Davis & Geller 1976; Guzzo et al. 1997; Zehavi et al. 2002; Hogg et al. 2003; Blanton et al. 2003; Einasto, et al. 2003a; Kauffmann et al. 2004; Mouhcine et al. 2007; Koyama et al. 2013). The formation and evolution of galaxies are known to be driven by accretion, tidal interaction, merger and various other secular processes. These physical processes are largely determined by the environment of the galaxies. The environment thus play a central role in the formation and evolution of galaxies and the study of the environmental dependence of the galaxy properties provides crucial inputs to the theories of galaxy formation and evolution.

A number of studies have been carried out to understand the environmental dependence of galaxy colour. The galaxy colour distribution is well fit with a double Gaussian distribution (Balogh, et al. 2004) which can be used to divide the galaxies into red and blue populations. It has been shown that the blue galaxies reside preferentially in low-density regions whereas the red galaxies inhabit the high-density regions (Hogg, et al. 2004; Baldry, et al. 2004; Blanton, et al. 2005; Ball, Loveday & Brunner 2008). Park, et al. (2007) find that the galaxy colour is nearly independent of local density when morphology and luminosity are fixed. Balogh, et al. (2004) show that when the luminosity is fixed, the fraction of galaxies in the red population is a strong function of local...
density. Cooper, et al. (2010) find a highly significant correlation between stellar age and environment at a fixed stellar mass for the red galaxies. Bamford et al. (2009) find that the galaxy colour is highly sensitive to environment at a fixed stellar mass. They reported that irrespective of morphology, the high stellar mass galaxies are mostly red in all environments whereas the low stellar mass galaxies are mostly blue in low density environment and red in high density environment.

Most of these studies use the local density as a proxy for the environment. Different methods are often used to define the environment based on the scale being probed (Muldrew, et al. 2012). The various environments of the cosmic web are characterized by the density as well as their morphology. The clusters represent the densest regions in the cosmic web followed by the filaments, sheets and voids. The galaxy clusters are the dense knots which reside at the intersection of elongated filaments. The filaments in the cosmic web are located at the intersection of sheets which encompass large empty regions or voids. Studies with N-body simulations (Aragón-Calvo, et al. 2010; Cautun, et al. 2014; Ramachandra & Shandarin 2015) suggest that matter successively flows from voids to walls, walls to filaments and then channelled along the filaments onto the clusters. The dark matter halos formed at various environments of the cosmic web are known to have different mass, shape and spin due to the influence of their large-scale environment (Hahn et al. 2007). The galaxies are assumed to form at the centre of these dark matter halos via cooling and condensation of baryons (White & Rees 1978). In the halo model, the mass of the dark matter halo is believed to be the single most important parameter which determines the properties of a galaxy (Cooray & Sheth 2002). However the clustering of the dark matter halos depend on their assembly history (Croton, Gao & White 2007; Gao & White 2007; Musso, et al. 2018; Vakili & Hahn 2019) besides their mass. This implies that the environmental dependence of the galaxy properties may extend beyond the local density and the large-scale environments in the cosmic web may impart significant influence on the formation and evolution of galaxies. However there are no universal measure for characterizing the large-scale environments in the cosmic web. Some of the existing statistical tools designed for this purpose are the Shapefinders (Sahni et al. 1998), the statistics of maxima and saddle points (Colombi, Pogosyan & Souradeep 2000), the multi-scale morphology filter (Aragón-Calvo et al. 2007), the skeleton formalism (Novikov et al. 2006) and the local dimension (Sarkar & Bharadwaj 2009).

In the present work, we use the local dimension (Sarkar & Bharadwaj 2009) to quantify the different environments in the cosmic web. A recent analysis with local dimension find that the sheets are the most prevalent pattern in the SDSS galaxy distribution which can extend up to \(90h^{-1}\) Mpc (Sarkar & Pandey 2019). They also show that the straight filaments extend only up to a length scale of \(30h^{-1}\) Mpc. The different structural components of the cosmic web differ in density, morphology and size. Each of these components provides an unique environment for galaxy formation and evolution. The role of the large-scale environment in this context is not yet settled. Luparello et al. (2015) find that the properties of the brightest group galaxies in the SDSS depend on their embedding large-scale structures. Using SDSS, Scudder et al. (2012) find that the star formation rates in isolated groups and the groups embedded in superstructures are significantly different. Yan, Fan & White (2013) analyze the SDSS data to find that the tidal environment of large scale structures do not influence the galaxy properties. Recently, Lee (2018) show that the elliptical galaxies in the sheetlike environment dwell in the regions with the highest tidal coherence. Pandey & Sarkar (2017) analyze the Galaxy Zoo (Lintott et al. 2008) data using information theoretic measures to find that morphology and environment exhibit a synergic interaction up to a length scales of \(\sim 30h^{-1}\) Mpc.

The Sloan Digital Sky Survey (SDSS) is the largest spectroscopic and photometric galaxy redshift survey to date. It provides an unprecedented view of the cosmic web by precisely mapping millions of galaxies in the nearby Universe. In the present work, we analyze the spectroscopic data from the SDSS DR16 (Ahumada, et al. 2019). The primary aim of the present work is to identify the galaxies in different environments of the cosmic web using local dimension and explore the variations of red and blue galaxy fractions and their average colours across these environments. This would reveal how the galaxy colour is influenced by the different environments in the cosmic web. At a fixed length scale, we study how the red and blue fractions and their average colours vary in different environments with increasing luminosity. We also study the bimodal nature of the colour distribution across different environments at different luminosities. Besides density and morphology, the size of the different structural components of the cosmic web may also play a role in shaping the colour of a galaxy. We address this by measuring the red and blue fractions and their average colours across different environments with increasing length scales keeping the luminosity of the galaxies fixed. The analysis presented in this work would help us to understand the environmental factors besides the local density which may influence the colour of galaxies.

We use a ΛCDM cosmological model with \(\Omega_m = 0.305\), \(\Omega_b = 0.695\) and \(h = 0.674\) to calculate distances from redshifts throughout the analysis.

A brief outline of the paper is as follows. The method of analysis and the data are described in Section 2 and Section 3 respectively. The results of the analysis are discussed in Section 4 and we present our conclusions in Section 5.
The radius of the largest sphere that would fit inside the survey region.

The galaxies are embedded in different morphological environments in the cosmic web and the number count $N(<R)$ around a galaxy is expected to scale as,

$$N(<R) = AR^D$$  \hspace{1cm} (1)

where $A$ is a constant and the exponent $D$ is the local dimension (Sarkar & Bharadwaj 2009). The local dimension $D$ tells us about the morphology of the embedding environment within a length scale range $R_1 h^{-1} \text{Mpc} \leq R \leq R_2 h^{-1} \text{Mpc}$. We consider only the centres for which there is at least 10 galaxies within this radius range. For each centre, we obtain the best fit values of $A$ and $D$ using the least-square fitting. We calculate the associated $\chi^2$ values using the observed and the fitted values of $N(<R)$. Only the galaxies for which the chi-square per degree of freedom $\frac{\chi^2}{\nu} \leq 0.5$ are considered in the present analysis. Ideally one would expect $D = 1$ for galaxies residing in filaments, $D = 2$ for the galaxies residing in sheets and $D = 3$ for the galaxies residing in a three dimensional volume. However the size and shape of these structures vary considerably within the cosmic web. Besides there would be galaxies in the intermediate environments (e.g. junction of a sheet and a filament). In this case the measuring sphere would incorporate multiple type of structures within it. We classify the environment of a galaxy in five different classes (Table 1) depending on their local dimension. We assign a specific range of local dimension to each class. The galaxies in class C1 are residing in filaments, whereas the C2 type galaxies are embedded in sheets. The C3 type galaxies are mostly field galaxies in the low density regions. The I1 type galaxies have intermediate local dimension between filaments and sheets whereas I2 galaxies have local dimension in between sheets and fields. The environment of a galaxy as indicated by its local dimension would depend on the length scales under consideration.

We isolate the galaxies in different environments and segregate them into red and blue populations in each environment based on their $u-r$ colour. We use an optimal colour cut $(u-r)=2.22$ prescribed by Strateva, et al. (2001) to classify the red and blue galaxies. The galaxies with $u-r<2.22$ are identified as blue whereas the ones with $u-r \geq 2.22$ are termed as red.

We calculate the fraction of red and blue galaxies in each environment on different length scales for each of the volume limited samples described in the next section. We prepare 10 jackknife samples from each volume limited sample to estimate the errorbars for our measurements. Each jackknife sample is prepared by randomly deleting 25% galaxies from the original sample.

### 3 DATA

The Sloan Digital sky survey (SDSS) is a multi band imaging and spectroscopic redshift survey which covers more than one third of the celestial sphere. We use data from the 16th data release (Ahumada, et al. 2019) of the Sloan Digital sky survey (SDSS). SDSS DR16 is the fourth and final data release of SDSS IV which incorporates data from all the prior data releases. We download the data from the SDSS SkyServer \(^1\) using Structured Query Language (SQL). For the present analysis, we select a contiguous region of the sky which spans $0^\circ \leq \delta \leq 60^\circ$ and $135^\circ \leq \alpha \leq 225^\circ$ where $\alpha$ and $\delta$ are the right ascension and declination respectively. We select all the galaxies with r-band Petrosian magnitude

\(^1\) https://skyserver.sdss.org/casjobs/
Table 1. This table shows the classification of the five types of galaxy environment based on their local dimension.

| Local dimension | Classified as | C1 | C2 | C3 |
|-----------------|---------------|----|----|----|
| 0.75 ≤ D < 1.25 | J1            |    |    |    |
| 1.25 ≤ D < 1.75 | J2            |    |    |    |
| 1.75 ≤ D < 2.25 | I1            | C2 |    |    |
| 2.25 ≤ D < 2.75 | I2            |    | C2 |    |
| D ≥ 2.75        | I3            |    |    | C3 |

Table 2. This table summarizes the four volume limited samples extracted from SDSS DR16.

| Volume limited samples | Absolute magnitude ($M_r$) | Redshift (z) | Number of galaxies | Number density ($h^3$Mpc$^{-3}$) | Mean inter-galactic separation ($h^{-1}$Mpc) | Radial size ($h^{-1}$Mpc) |
|------------------------|---------------------------|--------------|--------------------|-----------------------------------|-----------------------------------------------|---------------------------|
| Sample 1               | -20.5 ≥ $M_r$ ≥ -22.5     | 0.035 ≤ z ≤ 0.095 | 90270              | 9.72×10$^{-3}$                    | 4.69                                          | 174.40                    |
| Sample 2               | -21 ≥ $M_r$ ≥ -23         | 0.041 ≤ z ≤ 0.120 | 104137             | 5.61×10$^{-3}$                    | 5.63                                          | 227.93                    |
| Sample 3               | -21.5 ≥ $M_r$ ≥ -23.5     | 0.050 ≤ z ≤ 0.145 | 92848              | 2.90×10$^{-3}$                    | 7.01                                          | 271.47                    |
| Sample 4               | -19.5 ≥ $M_r$ ≥ -20.5     | 0.014 ≤ z ≤ 0.063 | 29366              | 1.00×10$^{-2}$                    | 4.64                                          | 145.39                    |

Figure 2. The top three and the bottom three panels of this figure respectively show the variations in the number and fraction of classified galaxies belonging to different types of environment (Table 1) as a function of $R_2$ for Sample 1, Sample 2 and Sample 3 (Table 2).

RESULTS

4.1 Variations of environments with length scale

The different environments of the cosmic web have different characteristic size and their abundance would depend on the length scales probed. We first quantify the number of classifiable galaxies in each type of environment. The top three panels of Figure 2 show the number of classified galaxies in different types of environment as a function of length scale in Sample 1, Sample 2 and Sample 3. The respective fraction of galaxies available at each type of environment on each length scale for the three volume limited samples are shown in the bottom three panels of the same figure. We choose $R_1 = 5h^{-1}$Mpc and then increase $R_2$ in uniform steps.
Galaxy colour and the cosmic web

Figure 3. This figure shows the fraction of red and blue galaxies in different environments of the cosmic web for different length scales for Sample 1, Sample 2 and Sample 3 (Table 2). The 1–σ error bars at each data point are calculated using 10 Jackknife samples drawn from each of the SDSS samples. The total number of classified galaxies at three different length scales for each of the samples are also mentioned in the respective panels.

of $5h^{-1}\text{Mpc}$ starting from $R_2 = 10h^{-1}\text{Mpc}$. The number of classifiable galaxies in each sample is expected to decrease with increasing $R_2$ due to their finite size.

In the bottom three panels of Figure 2, we find that the galaxies live in diverse environments on small scales. In each of the three volume limited samples, nearly $60-70\%$ galaxies reside in filaments and sheets when the environment is characterized within a length scale of $10-30h^{-1}\text{Mpc}$. The $C1$ type environments are mostly associated with the straight filaments which extend only upto $\sim 30h^{-1}\text{Mpc}$ in these samples. The galaxies which are part of the curved or warped filaments would be mostly represented by the $I1$ type galaxies. We find that the $I1$ type environment extends upto $\sim 50h^{-1}\text{Mpc}$. The fraction of $C1$ and $I1$ type galaxies steadily decrease with increasing length scales. The $C2$ type galaxies reside in sheets which are the most abundant environment within a scale of $\sim 30h^{-1}\text{Mpc}$. The abundance of sheet peaks around $20-30h^{-1}\text{Mpc}$ in all three volume limited samples. The fraction of galaxies in sheetlike environment decreases with increasing length scales and only $\sim 10-20\%$ galaxies are part of sheetlike structures at $70h^{-1}\text{Mpc}$. No galaxies are found to be a part of filamentary environment at this length scale. Comparison of the results from the three volume limited samples suggests that the filamentary and sheetlike environments can be traced to a slightly larger length scales in the brighter samples. This results from the larger number of classifiable galaxies available at larger length scales due to the bigger volumes of the brighter samples. At $70h^{-1}\text{Mpc}$, $80-90\%$ of the galaxies are part of $I2$ and $C3$ type environments which indicates that the diversity of environment ceases to exist on larger length scales. The fact that the local dimension of galaxies shift towards 3 hints towards the emergence of a homogeneous network of galaxies on sufficiently large length scales. This is consistent with the findings of various studies on large-scale homogeneity which suggests that the Universe is statistically homogeneous on scales beyond $\sim 100-150h^{-1}\text{Mpc}$ (Yadav et al. 2005; Hogg et al. 2005; Sarkar et al. 2009; Scrimgeour et al. 2012; Nadathur 2013; Pandey & Sarkar 2015; Pandey & Sarkar 2016; Avila et al. 2018).

4.2 Variations of red and blue fractions and their average colour with environment, luminosity and length scale

We show the fraction of red and blue galaxies in different environments of the cosmic web for Sample 1, Sample 2 and Sample 3 respectively in the top, middle and bottom panels.
of Figure 3. The left, middle and right panels at the top, middle and bottom row of Figure 3 corresponds to three different length scales $10h^{-1}\,\text{Mpc}$, $40h^{-1}\,\text{Mpc}$ and $70h^{-1}\,\text{Mpc}$ respectively. Thus each row in Figure 3 corresponds to a fixed luminosity and each column corresponds to a fixed length scale. At any fixed length scale, the fraction of red galaxies increases and the fraction of blue galaxies decreases in all environments with increasing luminosity of the samples. The top left panel of Figure 3 shows that for the Sample 1, $\sim 60\%$ galaxies are red and $\sim 40\%$ galaxies are blue in filamentary (C1 type) environment at $10h^{-1}\,\text{Mpc}$. The fractions of red and blue galaxies change to $\sim 75\%$ and $\sim 25\%$ respectively in this environment for the brightest sample as shown in the bottom left panel of the same figure. Similarly the fraction of red and blue galaxies in sheetlike environment (C2 type) at $10h^{-1}\,\text{Mpc}$ changes from $\sim 55\%$ and $\sim 45\%$ to $\sim 70\%$ and $\sim 30\%$ when we compare Sample 1 and Sample 3 respectively. The Figure 3 show that the fraction of red and blue galaxies in different environments change similarly in all the environments with the increasing luminosity. In Figure 4, we separately show the distributions of red and blue galaxies residing in sheets on $10h^{-1}\,\text{Mpc}$ in the first 3 of the volume limited samples analyzed. The figure shows that the redder galaxies populate the denser parts of the sheets at each luminosity. The relative increase in red galaxies compared to the blue galaxies in sheetlike environment with increasing luminosity of the samples can be also clearly seen in Figure 4.

The same trend is observed for all the other types of environment in Figure 3. The C3 type environment has a slightly higher fraction of blue galaxies in Sample 1. In the top left, middle left and bottom left panels of Figure 3, we find that environments with smaller local dimension tend to host a slightly higher fraction of red galaxy. The increase in the red fraction with increasing luminosity and decreasing local dimension becomes more pronounced on larger length scales as can be seen in the middle and right panels of the same figure. We estimate the average colour of the red and blue galaxies in each type of environment for 3 different length scales for each of the 3 volume limited samples. The corresponding results are shown in Figure 5. We note that the average colour of the red and blue galaxies in all environments for each of these samples increases with increasing luminosity. The average colour of galaxies is also found to mildly increase with decreasing local dimension at each length scale for each sample.

It may be noted that the straight filaments in these samples extend only up to $\sim 30h^{-1}\,\text{Mpc}$ and there are very few galaxies which can be part of C1 type environment at $40h^{-1}\,\text{Mpc}$. The larger error-bars corresponding to the C1 type environment on length scale of $40h^{-1}\,\text{Mpc}$ in Figure 3 and Figure 5 result from smaller number of galaxies present...
Figure 5. The different panels of this figure show the average colour of red and blue galaxies in different environments of the cosmic web on different length scales for Sample 1, Sample 2 and Sample 3 (Table 2). The $1-\sigma$ error bars at each data point are calculated using 10 Jackknife samples drawn from each of the SDSS samples.

Figure 6. This figure compares the corrected and uncorrected fraction of red and blue galaxies residing in sheets (C2 type) of different size in Sample 1, Sample 2 and Sample 3 (Table 2).

The Figure 3 shows that the fraction of red and blue galaxies also depends on the length scales associated with the environment. At a fixed luminosity and a fixed environment, the fraction of red galaxies increases with increasing length scales. We show the fraction of red and blue galaxies residing in sheets as a function of their size in the first 3 volume limited samples in Figure 6. The figure clearly shows that there is an increase in the fraction of red galaxies and a decrease in the fraction of blue galaxies with the increasing size of these structures. It is worthwhile to mention here that a subset of galaxies can be identified in the same type of environment on multiple length scales. These galaxies are part of such environment which extends at least upto the largest among these length scales. This must be taken into account while estimating the fraction of red or blue populations in different environments. We quantify the number of such galaxies at each environment for all the samples. For example, the number of such galaxies in C2
type environment for different length scales are tabulated in Table 4. This table shows that in Sample 1, there are 181 galaxies which reside in sheets at all three length scales i.e. $10h^{-1}\text{Mpc}$, $40h^{-1}\text{Mpc}$ and $70h^{-1}\text{Mpc}$. These 181 galaxies are part of sheets extending to at least $70h^{-1}\text{Mpc}$. Further, 2812 galaxies are part of sheets both at $10h^{-1}\text{Mpc}$ and $40h^{-1}\text{Mpc}$ but not at $70h^{-1}\text{Mpc}$. These galaxies are part of sheets which are extended upto $40h^{-1}\text{Mpc}$. We subtract these two numbers from the total number of galaxies identified in sheets on $10h^{-1}\text{Mpc}$. Similarly, 411 galaxies are identified in C2 type environment both at $40h^{-1}\text{Mpc}$ and $70h^{-1}\text{Mpc}$ in Sample 1. The sheets associated with these galaxies extend at least upto $70h^{-1}\text{Mpc}$. We subtract this number from the total number of galaxies found in sheets on a length scale of $40h^{-1}\text{Mpc}$. The red and blue fractions in C2 type environment are also corrected in Sample 2 and Sample 3 in a similar manner. We show both the corrected and the uncorrected fractions of red and blue galaxies in sheetlike environment at different length scales in Figure 6. We find that these corrections hardly make any difference to these results.

Figure 3 shows that nearly all the environments in the cosmic web are dominated by red galaxies. However Sample 1, Sample 2 and Sample 3 consist of fairly brighter galaxies and this may not be the case for the fainter galaxies. To test this, we construct a volume limited sample namely the Sample 4 (Table 2) which contains galaxies which are fainter than the other 3 samples. Sample 4 covers a smaller volume and we could not probe the environments on the same length scales as done for the other three samples. We probe the different environments in this sample for 3 different length scales $10, 20$ and $30h^{-1}\text{Mpc}$. The fraction of red and blue galaxies in different environments at these length scales for Sample 4 are shown in Figure 7. We find that at $10h^{-1}\text{Mpc}$, all the environments are dominated by blue
Table 3. This table shows the number of classified galaxies in different environments in first three volume limited samples (Table 2) for three different values of $R_2$.

| Sample Name | Total galaxies | Number of galaxies classified at $R_2 h^{-1}$Mpc |
|-------------|----------------|-----------------------------------------------|
|             | $R_2 = 10$    | $R_2 = 40$ | $R_2 = 70$ |
| Total:      | 71634         | 29971     | 5089     |
| Sample 1    | 90270         |           |          |
| C1:         | 6362          | 0         | 0        |
| I1:         | 19229         | 951       | 0        |
| C2:         | 21060         | 8464      | 497      |
| I2:         | 13213         | 13037     | 3100     |
| C3:         | 11770         | 7519      | 1492     |
| Total:      | 82073         | 41820     | 15053    |
| Sample 2    | 104137        |           |          |
| C1:         | 11167         | 25        | 0        |
| I1:         | 23630         | 1483      | 90       |
| C2:         | 22479         | 12972     | 1820     |
| I2:         | 13207         | 17749     | 8370     |
| C3:         | 11590         | 9591      | 4773     |
| Total:      | 67673         | 43578     | 20212    |
| Sample 3    | 92848         |           |          |
| C1:         | 12109         | 55        | 0        |
| I1:         | 20717         | 2444      | 144      |
| C2:         | 17177         | 15700     | 3999     |
| I2:         | 9496          | 17519     | 11153    |
| C3:         | 8174          | 7860      | 4916     |

Table 4. This table shows the number of centres which are available at sheetlike environment on multiple length scales for the first 3 volume limited samples.

| Sample Name | Number of C2 type galaxies which are common at $R_2 = 10$ and $40 h^{-1}$Mpc | Number of C2 type galaxies which are common at $R_2 = 10$, 40 and 70$h^{-1}$Mpc | Number of C2 type galaxies which are common at $R_2 = 40$ and 70$h^{-1}$Mpc |
|-------------|-----------------------------------------------------------------------------|---------------------------------------------------------------------------|--------------------------------------------------------------------------|
| Sample 1    | 2812                                                                         | 181                                                                        | 411                                                                       |
| Sample 2    | 3352                                                                         | 568                                                                        | 1219                                                                      |
| Sample 3    | 3126                                                                         | 1084                                                                       | 2890                                                                      |

Galaxies which is exactly opposite to what were observed for the other three samples. However the fraction of red galaxies in Sample 4 also decreases with the increasing local dimension like the other three samples. The middle and right panels of Figure 7 show that the same trend persists for each of the length scales. The change in the fraction of red and blue galaxies in C2 type environment for three different length scales in Sample 4 are shown in Figure 8. A comparison between Figure 8 and Figure 6 shows that the fraction of red galaxies in sheets on $10 h^{-1}$Mpc is $\sim 35\%$ for Sample 4 whereas the brightest sample (Sample 3) host $\sim 70\%$ red galaxies in sheets on the same length scale. The fraction of red galaxies in a fixed environment and fixed length scale depends on the luminosity of the galaxies. These figures also show that the fraction of red galaxies in sheetlike environment increases with the increasing length scales. The dependence of red and blue fractions on the local dimension and the length scales are same in all the samples considered in this analysis. In Figure 3, the red and blue fractions in each environment at each length scale exhibit a vertical shift in opposite direction with increasing luminosity. The dominance of the blue population in different environments for Sample 4 (Figure 7) is associated with the lower luminosity of the galaxies in this sample. Figure 7 and Figure 3 together show that the red and the blue curves move towards each other, cross each other and then move away from each other with increasing luminosity.

4.3 Bimodality of the colour distribution in different environments and luminosity

Galaxy colour is known to follow a bimodal distribution. We fit the distribution of the $u-r$ colour of galaxies using a
The different panels of this figure shows the distribution of $u-r$ colour in C1, C2 and C3 type environment on $10h^{-1}$Mpc size in Sample 1, Sample 2 and Sample 3. The total number of galaxies identified in different environments on $10h^{-1}$Mpc for each samples are provided in the respective panels. The solid blue line in each panel represent the best fit double Gaussian describing the $u-r$ colour distribution. The best fit parameters of the double Gaussian distribution for each case are tabulated in Table 5.

We plot the distributions of $u-r$ colour in C1, C2 and C3 type environments on a length scale of $10h^{-1}$Mpc for Sample 1, Sample 2 and Sample 3 in different panels of Figure 9. We fit each of these distributions using a two Gaussian distribution (Equation 2). The fitted parameters corresponding to the colour distributions at 3 different environments for 3 luminosity bins are tabulated in Table 5. In each panel, the left and right peaks of the bimodal distribution corresponds to the blue and red galaxies respectively. At each environment and each luminosity, the colour distribution of the blue galaxies is broader than that of the red galaxies. On the other hand, the amplitude associated with the colour distribution of the red galaxies is higher than that of the blue galaxies in each case. The mean of the distributions for blue and red galaxies are sensitive to the environment and luminosity of galaxies. The mean increases with increasing luminosity and decreases with increasing local dimension. At any fixed luminosity, the amplitude of the distribution corresponding to the red galaxies increases with decreasing local dimension. On the other hand, the amplitude of the distribution for blue galaxies decreases with decreasing local dimension. This clearly shows that red galaxies prefer to reside in the environments with smaller local dimension. At any fixed environment, the increase in luminosity is respectively associated with an increase and decrease in the amplitudes of the distributions for the red and blue galaxies. The width of the distribution corresponding to the blue population decreases whereas that for the red population increases with the increasing luminosity. These indicate that more luminous galaxies tend to be redder. Both these findings are consistent with Figure 3 which show a similar dependence of the red and blue fraction on the local dimension and luminosity. Despite these variations across different environments and luminosities, the valley which separates the blue and red distributions appear around the same colour cut $(u-r) = 2.22$ used to separate the two distributions. Finally, Figure 9 shows that the bimodal nature of the colour distribution is present across all environments and luminosities.

We could not repeat this analysis for $R_2 = 40h^{-1}$Mpc and $R_2 = 70h^{-1}$Mpc due to a relatively smaller number of galaxies available at these environments on those length scales.
5 CONCLUSIONS

We study the dependence of galaxy colour on different environments of the cosmic web using the data from SDSS DR16. We analyze a number of volume limited samples with different luminosity. We isolate the galaxies in different environments by quantifying their local dimension on different length scales. We estimate the fraction of red and blue galaxies by quantifying the local dimension on different length scales. We isolate the galaxies in different environments by quantifying their local dimension on different length scales. In the present analysis, the environments with lower local dimension and higher luminosity favour the transformation from blue to red galaxies. Consequently a greater fraction of galaxies in the larger structures would have redder colour. It may be noted that a large fraction of the red galaxies are known to be spirals (Masters, et al. 2010) which reside in filamentary and sheetlike environments of the cosmic web.

We also note that the average colour of galaxies becomes redder with decreasing local dimension of the host environment and increasing luminosity of the sample. The distribution of galaxy colour in each environment can be described by a double Gaussian. We find that the amplitude and the width of the two Gaussian components associated with the red and blue galaxies are sensitive to the local dimension and luminosity in such a way which indicates that the environments with lower local dimension and higher luminosity favour the transformation from blue to red galaxies. However the bimodal nature of the colour distribution persists in all environments at all luminosities which suggests that such transformations are possible in all environments possibly via different physical processes.

Finally, we would like to emphasize that the colour of a galaxy depends on the size of its host environment besides density and luminosity. The present analysis shows that the larger structures contain a higher fraction of red galaxies and a lower fraction of blue galaxies. Superclusters are known to have a sheetlike morphology with an interven-

| Sample 1 | Environment | $\mu_1$ | $\mu_2$ | $\sigma_1$ | $\sigma_2$ | $A_1$ | $A_2$ |
|----------|-------------|---------|---------|------------|------------|-------|-------|
| C1 type  | 1.8867 ± 0.0166 | 2.5922 ± 0.0059 | 0.3287 ± 0.0157 | 0.2035 ± 0.0051 | 0.0164 ± 0.0004 | 0.0315 ± 0.0006 |
| C2 type  | 1.8844 ± 0.0133 | 2.6058 ± 0.0049 | 0.3448 ± 0.0128 | 0.2004 ± 0.0044 | 0.0171 ± 0.0003 | 0.0295 ± 0.0005 |
| C3 type  | 1.8366 ± 0.0110 | 2.5731 ± 0.0068 | 0.3271 ± 0.0107 | 0.2077 ± 0.0060 | 0.0209 ± 0.0003 | 0.0242 ± 0.0005 |

| Sample 2 | Environment | $\mu_1$ | $\mu_2$ | $\sigma_1$ | $\sigma_2$ | $A_1$ | $A_2$ |
|----------|-------------|---------|---------|------------|------------|-------|-------|
| C1 type  | 1.9667 ± 0.0194 | 2.6564 ± 0.0063 | 0.3249 ± 0.0175 | 0.2083 ± 0.0053 | 0.0155 ± 0.0004 | 0.0321 ± 0.0007 |
| C2 type  | 1.9233 ± 0.0163 | 2.6428 ± 0.0066 | 0.3176 ± 0.0146 | 0.2259 ± 0.0054 | 0.0158 ± 0.0003 | 0.0298 ± 0.0005 |
| C3 type  | 1.8946 ± 0.0127 | 2.6223 ± 0.0074 | 0.3148 ± 0.0118 | 0.2213 ± 0.0063 | 0.0194 ± 0.0003 | 0.0256 ± 0.0005 |

| Sample 3 | Environment | $\mu_1$ | $\mu_2$ | $\sigma_1$ | $\sigma_2$ | $A_1$ | $A_2$ |
|----------|-------------|---------|---------|------------|------------|-------|-------|
| C1 type  | 1.9658 ± 0.0211 | 2.7099 ± 0.0081 | 0.2885 ± 0.0186 | 0.2487 ± 0.0068 | 0.0134 ± 0.0004 | 0.0315 ± 0.0005 |
| C2 type  | 1.9620 ± 0.0176 | 2.6937 ± 0.0081 | 0.2849 ± 0.0151 | 0.2553 ± 0.0067 | 0.0147 ± 0.0004 | 0.0296 ± 0.0004 |
| C3 type  | 1.9052 ± 0.0171 | 2.6611 ± 0.0110 | 0.2824 ± 0.0144 | 0.2735 ± 0.0092 | 0.0170 ± 0.0004 | 0.0258 ± 0.0005 |
ing filamentary environment (Costa-Duarte, Sodrée & Durret 2011; Einasto, et al. 2011, 2017). Einasto, et al. (2014) reported a higher fraction of red galaxies in filament-type superclusters. It would be also interesting to study the abundance and distribution of the red and blue galaxies in the individual superclusters of different size. Further, the recent studies with the Galaxy Zoo reveal that a large number of red galaxies are massive spirals (Bamford et al. 2009; Masters, et al. 2010; Tojeiro, et al. 2013). Masters, et al. (2010) find that the local density alone is not sufficient to explain the colour of these galaxies. They reported that the massive galaxies are red independent of their morphology.

The results of the present analysis suggests that if the massive red spirals are hosted in larger filaments or sheets then their colour may be explained by their embedding large-scale environment which favours a higher accretion rate leading to a larger stellar mass and consequently a faster depletion of the surrounding gas reservoir. In future, we plan to carry out such an analysis with the Galaxy Zoo which would help us to better understand the role of the embedding large-scale structures on the galaxy formation and evolution.

6 ACKNOWLEDGEMENT

BP would like to acknowledge financial support from the SERB, DST, Government of India through the project CRG/2019/001110. BP would also like to acknowledge IUCAA, Pune for providing support through associateship programme. SS would like to thank UGC, Government of India for providing financial support through a Rajiv Gandhi National Fellowship. SS would also like to acknowledge Biswajit Das for useful discussions.

The authors would like to thank the SDSS team for making the data public. Funding for the Sloan Digital Sky Survey IV has been provided by the Alfred P. Sloan Foundation, the U.S. Department of Energy Office of Science, and the Participating Institutions. SDSS-IV acknowledges support and resources from the Center for High-Performance Computing at the University of Utah. The SDSS web site is www.sdss.org.

SDSS-IV is managed by the Astrophysical Research Consortium for the Participating Institutions of the SDSS Collaboration including the Brazilian Participation Group, the Carnegie Institution for Science, Carnegie Mellon University, the Chilean Participation Group, the French Participation Group, Harvard-Smithsonian Center for Astrophysics, Instituto de Astrofísica de Canarias, The Johns Hopkins University, Kavli Institute for the Physics and Mathematics of the Universe (IPMU) / University of Tokyo, the Korean Participation Group, Lawrence Berkeley National Laboratory, Leibniz Institut für Astrophysik Potsdam (AIP), Max-Planck-Institut für Astronomie (MPIA Heidelberg), Max-Planck-Institut für Astrophysik (MPA Garching), Max-Planck-Institut für Extraterrestrische Physik (MPE), National Astronomical Observatories of China, New Mexico State University, New York University, University of Notre Dame, Observatório Nacional / MCTI, The Ohio State University, Pennsylvania State University, Shanghai Astronomical Observatory, United Kingdom Participation Group, Universidad Nacional Autónoma de México, University of Arizona, University of Colorado Boulder, University of Oxford, University of Portsmouth, University of Utah, University of Virginia, University of Washington, University of Wisconsin, Vanderbilt University, and Yale University.

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