Galaxy interactions in different environments: An analysis of galaxy pairs from the SDSS

Apashanka Das, a Biswajit Pandey, a Suman Sarkar, b and Arunima Dutta a

a Department of Physics, Visva-Bharati University, Santiniketan, 731235, India
b Department of Physics, Indian Institute of Science Education and Research Tirupati, Tirupati - 517507, Andhra Pradesh, India
E-mail: a.das.cosmo@gmail.com, biswap@visva-bharati.ac.in, suman2reach@gmail.com, aru.megha@gmail.com

Abstract. We analyze the galaxy pairs in a volume limited sample ($M_r \leq -21$) from the SDSS to study the effects of galaxy interactions on the star formation rate and colour of galaxies in different environments. We study the star formation rate and colour of the paired galaxies as a function of projected separation and compare the results with their control samples matched in stellar mass, redshift and local density. We find that the major interactions significantly enhance the star formation rate in paired galaxies and turn them bluer with decreasing pair separation within $30$ kpc. The impact of tidal interactions on star formation rate and colour are more significant in the heavier members of the major pairs. The star formation enhancement in major pairs is significantly higher at the low-density environments, where the influence can extend up to $\sim 100$ kpc. Contrarily, the major pairs at high-density environments show suppression in their star formation. Depending on the embedding environments, the major interactions in the intrinsically brighter galaxy pairs can thus enhance or quench star formation. We find that the minor pairs at both low-density and high-density environments are significantly less star-forming and redder than their control galaxies. It indicates that the minor interactions in intrinsically brighter galaxy pairs always suppress the star formation irrespective of their environment. The lighter members in these minor pairs show a greater susceptibility to suppressed star formation. Our results imply that both the major and minor interactions can contribute to the observed bimodality. We conclude that the galaxy evolution is determined by a complex interplay between the galaxy properties, galaxy interactions, and environment.
1 Introduction

Understanding the origin of the galaxies and their evolution is one of the most challenging goals of modern cosmology. It remains one of the most active and fertile areas of research in the last few decades. In the current paradigm, the primordial density fluctuations in the dark matter density field collapse into dark matter halos, forming the first bound objects. These dark matter halos accrete neutral hydrogen gas from their surrounding environment that eventually leads to the formation of galaxies at their centres by the cooling and condensation [1–4]. In this picture, the gas accretion from the intergalactic medium (IGM) is the primary mechanism responsible for the growth of a galaxy. The subsequent formation of a supermassive black hole at the centre of the galaxy and an efficient accretion onto it can trigger AGN activity. The jet from the AGN, starburst winds and supernovae explosions can drive gas outflows from the galaxy. The gas ejected from the galaxy eventually cools down and reaccrates again to continue the cycle. The interplay between these processes and their equilibrium are important in galaxy evolution. However, the evolutionary history of a galaxy is not entirely determined by these processes alone.

The observations suggest a significant evolution of galaxy properties in the recent past. The cosmic star formation declines by an order of magnitude between \( z = 1 \) to \( z = 0 \) [5]. It is now well known that the number of red galaxies and their stellar mass are steadily increasing since \( z \sim 1 \) [6, 7]. On the other hand, the stellar mass in the blue galaxies remains nearly the same during this period [7–9]. These observational results can be understood if the blue star-forming galaxies transform into red galaxies via quenching of star formation, and the galaxies in the blue cloud experience an enhanced star formation.

It is important to remember that the galaxies are not island universes that evolve in isolation. They are an integral part of a more extensive and complex network, namely the cosmic web [10]. Both initial conditions and interactions with the small and large scale environment play crucial roles in their formation and evolution. In the hierarchical scenario, the galaxy interactions and mergers provide an efficient mechanism for the buildup of massive galaxies. Such processes can modify the mass distribution and morphology of galaxies and trigger star formation activity. Using simulations of tidal interactions, Toomre & Toomre
first showed that the spiral and irregular galaxies could transform into ellipticals and S0 galaxies. Subsequent studies with more sophisticated simulations revealed that the tidal torques generated during the encounter act upon the misaligned gaseous and stellar bars that allows the stellar component to remove angular momentum from the gas. The outward transfer of angular momentum activates gas inflows towards the centre of the galaxy. The rapid increase in gas density near the centre triggers a starburst that can efficiently convert the available gas reservoir into stars. The efficiency of this tidally triggered star formation is known to depend on several factors such as the amount of available gas, depth of the potential well, morphology, orbital parameters and the internal dynamical properties of galaxies.

The simulations of galaxy interactions suggest that the gravitational tidal torque generated during the interaction is more potent in galaxy pairs with similar stellar mass or luminosity. The large-scale gas inflows resulting from such interactions trigger new star formation in these galaxies. These interactions are known as the major interactions. The interactions between galaxies with a larger mass or luminosity contrast are known as minor interactions. It is well known that the frequency of dark matter halo mergers increases with the mass ratio. So the minor interactions and mergers are more frequent in a galaxy’s history. They are also known to play an essential role in triggering star formation and growth of galaxies in the semi-analytic models. Studies with simulations indicate that a lower level of star formation enhancement may also occur in minor mergers after several billion years. The induced star formation in minor interactions and mergers are known to depend on the structural and orbital parameters of the galaxies.

The first observational evidence of enhanced star formation in interacting galaxies came from a seminal study of optical colours in the morphologically disturbed galaxies. Many further studies of interacting galaxy pairs from the modern spectroscopic redshift surveys have now confirmed the SFR enhancement at smaller pair separation. The level of enhancement reported in most of these studies is within a factor of two compared to the isolated galaxies. The enhancement is known to depend on multiple factors such as the separation, luminosity or mass ratio and the type of galaxies involved in the interaction. The projected separation between the members in a pair is the most widely used indicator of the merger phase of a galaxy pair. The pairs at smaller separation are most likely undergoing a close passage, thereby triggering a starburst. On the other hand, the pairs at larger separation are believed to be receding away after their first pericentric passage and hence show a lower efficiency of star formation. However, these are difficult to confirm as the projected separation corresponds to a snapshot view of the interaction and does not provide any direct information about the time scale.

Most of the observational studies of galaxy pairs confirm the tidally triggered star formation in major interactions. However, the issue of star formation enhancement in minor interactions are less clear. In the hierarchical galaxy formation model, most interactions and mergers occur between unequal-mass systems due to the greater abundance of low mass and low luminosity galaxies. The minor interactions may thus play a crucial role in galaxy evolution. Any observational study of minor interaction and merger is challenging due to several reasons. The number of minor pairs identified from magnitude limited surveys are far less than the number of major pairs as the galaxies have similar magnitudes in such surveys. It is also difficult to identify the low-luminosity companions around the more luminous members due to the contaminations from the background galaxies. Despite these limitations, the effects of minor interactions on star formation have drawn considerable interest.
et al. [33] study the star formation enhancement in paired galaxies using 2dFGRS and find a dependence on the relative luminosity of the pairs. Nikolic et al. [35] use SDSS to analyze the star formation in paired galaxies and find no dependence on the luminosity of the companion galaxy. Woods et al. [37] analyze data from cfA2 survey and a follow-up search to find that the star formation enhancement in pairs decreases with increasing stellar mass ratio. Woods & Geller [38] show that the specific SFR of the less massive member in a minor pair is enhanced, whereas the more massive member remains unaffected. Ellison et al. [40] analyze the SDSS data and find tentative evidence for higher SFR for the less massive companions in minor pairs at a low significance level. Li et al. [51] also reached a similar conclusion using the SDSS data. Scudder et al. [52] study the SFR enhancements in SDSS galaxy pairs and find that both major and minor mergers show significant SFR enhancements. Kaviraj et al. [53] find that the minor mergers may induce moderate star formation in early-type galaxies at low redshift. Lambas et al. [54] show that the minor mergers are roughly two times less efficient in forming new stars than the major mergers.

The galaxies grow in mass by smooth accretion, accretion from companions and mergers with other galaxies. The observational signatures of major interactions and mergers are well understood. But our current understanding of the impact of minor interactions and mergers are far from complete. Observational studies indicate a low level of star formation enhancement in the less massive members of the pairs. However, it is unclear if the SFR enhancement in minor interactions is equally effective at all luminosities. The ratio of luminosity or mass may not wholly decide the SF activity in minor pairs. The exact ratio of the stellar mass or luminosity may affect the induced star formation differently in separate luminosity ranges and environments. Most of the earlier studies on galaxy pairs primarily focus on star-forming galaxies. It would be also interesting to know the effectiveness of tidal interaction in triggering star formation in the intrinsically more luminous galaxy pairs with relatively lower star formation.

The environments of galaxies are known to play a driving role in the formation and evolution of galaxies [55–76]. The star formation activity is known to get suppressed in the high-density regions [64, 77, 78]. The environment can quench star formation in galaxies through ram pressure stripping [79], galaxy harassment [80, 81], strangulation [79, 82] and starvation [47, 83, 84]. The same is also true for the efficiency of star formation in galaxy pairs in the denser environments. The tidal interactions in such environments can cause gas loss through starburst, AGN or shock-driven winds [85–87]. Perez et al. [88] find that the red fraction in galaxy pairs increases at intermediate density that indicates an efficient pre-processing by close encounters in such environments. In general, the galaxy pairs inhabit relatively denser regions compared to the isolated galaxies. It is possible to attribute the observed differences in the paired and isolated galaxies simultaneously to the tidal interaction and the environment, leading us to an age-old problem of “nature versus nurture” in galaxy formation and evolution. Although the control sample of the isolated galaxies is often constructed by matching the stellar mass and environment, it would be interesting to know the influence of major and minor interactions on the colour and star formation activity of the galaxies in the high and low-density regions of the cosmic density field. Most of the earlier studies on galaxy interactions analyzed flux-limited samples. It is difficult to meaningfully define the local physical environment around galaxy pairs in a flux limited sample. This can be more reliably estimated in a volume limited sample. We plan to use a volume limited sample for the present work.

The Sloan Digital Sky Survey (SDSS) [89] is the largest photometric and spectroscopic
redshift survey available at present. The availability of precise spectroscopic information for a large number of galaxies in the SDSS provides an excellent opportunity for the statistical study of galaxy interactions and their effects on the star formation and colour. The galaxy colour is strongly correlated with the star formation due to the observed bimodality [90, 91]. The galaxies in the blue cloud are gas rich and they have higher star formation rates. Contrarily, the red sequence hosts the gas poor galaxies with very low to no star formation. The tidal interactions between galaxies may trigger starbursts and consequently can alter their colours. Such colour changes usually happen on a time scale longer than the starburst. The effect of tidal interactions on the galaxy pairs can be captured more convincingly if we employ both star formation and colour for such studies. We plan to study the star formation rate and the dust corrected \((u - r)\) colour of the galaxy pairs in a volume limited sample from the SDSS, as a function of the projected separation and then compare them with the same from control samples of the isolated galaxies. The control samples will be prepared by simultaneously matching the stellar mass, local density and redshift of the paired galaxies. We want to study the colour and star formation activity of the major and minor pairs in both the low-density and high-density regions that would allow us to understand the relative role of tidal interaction and the environment in deciding these galaxy properties.

The outline of the paper is as follows. We describe the data and the method of analysis in Section 2, discuss the results in Section 3 and present our conclusions in Section 4.

Throughout the paper we use the \(\Lambda\)CDM cosmological model with \(\Omega_{m0} = 0.315\), \(\Omega_{\Lambda0} = 0.685\) and \(h = 0.674\) [92] for conversion of redshifts to comoving distance.

2 DATA AND METHOD OF ANALYSIS

2.1 SDSS DR16

The Sloan Digital Sky Survey (SDSS) is a multi-band imaging and spectroscopic redshift survey with a 2.5 m telescope at Apache Point Observatory in New Mexico. The technical details of the SDSS telescope is described in Gunn et al. [93] and a description of the SDSS photometric camera can be found in Gunn et al. [94]. The selection algorithm for the SDSS Main galaxy sample is discussed in Strauss et al. [89] and a technical summary of the survey is provided in York et al. [95].

We use the sixteenth data release (DR16) of the SDSS to identify the galaxy pairs in the nearby universe. We use structured query language (SQL) to download the spectroscopic and photometric information of galaxies in DR16 [96] from the SDSS CasJobs 1. We select a contiguous region of the sky spanned by the equatorial coordinates \(135^\circ \leq \alpha \leq 225^\circ\) and \(0^\circ \leq \delta \leq 60^\circ\) for our analysis and construct a volume limited sample by restricting the \(r\)-band apparent magnitude to \(m_r < 17.77\) and the absolute \(r\)-band Petrosian magnitude to \(M_r \leq -21\). The resulting sample extends up to \(z \leq 0.115\) and consists of 92102 galaxies.

We obtain the stellar mass and the star formation rate (SFR) of the galaxies from the StellarMassFSPSGranWideNoDust table. These are calculated using the Flexible Stellar Population Synthesis (FSPS) model [97]. The effects of the fibre aperture in these measurements are appropriately taken into account by using the aperture correction schemes described in Brinchmann et al. [98]. We retrieve the information of internal reddening E(B-V) of the galaxies from emissionLinesPort table which is based on publicly available Gas AND Absorption Line Fitting (GANDALF) [99] and penalised PIXEL Fitting (pPXF) [100]. Throughout this analysis, we have used dust corrected \(u - r\) colour of the galaxies.

1https://skyserver.sdss.org/casjobs/
Figure 1. The left panel shows the projected separation $r_p$ versus mean redshift of galaxy pairs with angular separation $< 55''$ (blue dots) and $> 55''$ (red dots) before culling. The black demarcation line corresponds to an angular separation of 55''. The right panel shows the same but after the culling procedure.

2.2 Identification of galaxy pairs

We identify the galaxy pairs using the traditional method based on the application of simultaneous cuts on the projected separation and the velocity difference.

We find the projected separation ($r_p$) between any of the two galaxies in the distribution. We calculate the projected separation from the redshift of the galaxies using the following relation

$$r_p = \frac{1}{2} (z_1 + z_2) \frac{c}{H_0} \theta$$

(2.1)

, where $z_1$ and $z_2$ are the redshifts of the galaxies in pair, $c$ and $H_0$ carry their usual meaning and $\theta$ is their angular separation given by

$$\theta = \cos^{-1} [\cos \delta_1 \cos \delta_2 \cos (\alpha_1 - \alpha_2) + \sin \delta_1 \sin \delta_2] .$$

(2.2)

Here $(\alpha_1, \delta_1)$ and $(\alpha_2, \delta_2)$ are the equatorial co-ordinates of the two galaxies considered.

The difference between the Hubble velocities of the two galaxies is

$$\Delta v = c |z_1 - z_2| .$$

(2.3)

In order to select the galaxy pairs, we impose simultaneous cuts on the projected separation and the velocity difference of the two galaxies under consideration. Any two galaxies are considered to form a pair if their projected separation $r_p < 0.5$ Mpc and the velocity difference $\Delta v < 300$ km/s. It is known from earlier studies that the pairs with $\Delta v > 500$ km/s are not likely to be gravitationally bound [101, 102] and interacting. We choose a somewhat larger cut-off for the projected separation to explore the effects of spurious pairs on larger scales.

An earlier work by Scudder et al. [52] show that excluding the galaxies with multiple companions do not alter their results. So we have allowed a single galaxy to be part of multiple pairs provided they satisfy the criteria imposed on $r_p$ and $\Delta v$.

We identify all the galaxy pairs within the same contiguous region and redshift as the volume limited sample described earlier. The pair selection algorithm, when applied to this
Figure 2. The top left, middle left, and bottom left panels, respectively show the probability distributions of redshift, $\log(M_{\text{stellar}}/M_{\odot})$ and local density for the pair and control galaxies. The corresponding cumulative distribution functions are compared in the top right, middle right and bottom right panels respectively.
### Table 1

This table shows the Kolmogorov-Smirnov statistic $D_{KS}$ for comparisons of redshift, $\log(M_{stellar}/M_{sun})$ and local density of pair and control galaxies. The table also lists the critical values $D_{KS}(\alpha)$ above which null hypothesis can be rejected at different confidence levels.

|                | $D_{KS}$ | Confidence level | $D_{KS}(\alpha)$ |
|----------------|----------|------------------|------------------|
| Redshift       | 0.0120   | 99%              | 0.0288           |
|                |          | 90%              | 0.0216           |
|                |          | 80%              | 0.0190           |
|                |          | 70%              | 0.0172           |
|                |          | 60%              | 0.0159           |
|                |          | 50%              | 0.0147           |
|                |          | 40%              | 0.0137           |
| $\log(M_{stellar}/M_{sun})$ | 0.0084 |                |                  |
|                | 70%      | 0.0172           |                  |
|                | 60%      | 0.0159           |                  |
|                | 50%      | 0.0147           |                  |
|                | 40%      | 0.0137           |                  |
| Local density  | 0.0105   | 30%              | 0.0128           |

region, yields a total 114070 galaxy pairs. We then cross match the galaxies in the volume limited sample with the galaxies in pairs that provides us with a total 11287 galaxy pairs present in our volume limited sample. We ensure that the matched galaxies in pairs must have measurements of the stellar mass, star formation rate and internal reddening. We then impose another cut so as to only consider the pairs with stellar mass ratio $< 10$. This restriction reduces the available number of galaxy pairs to 11200.

### 2.3 SDSS fibre collision effect: culling pairs

It is important to take into account the spectroscopic incompleteness due to the finite size of the SDSS fibres. The minimum separation of the fibre centres is 55′′ due to their finite size [89]. Consequently, the companion galaxies closer than 55′′ are preferentially missed leading to under-selection of the close angular pairs. The galaxies within the collision limit can be still observed if they lie in the overlapping regions between adjacent plates. The ratio of spectroscopic to photometric pairs decreases from $\sim 80\%$ at $> 55''$ to $\sim 26\%$ at lower angular separation [103]. This incompleteness effect can be compensated by randomly culling 67.5% of galaxies in pairs with the angular separation $> 55''$ [40, 46, 52].

We have 11200 galaxy pairs in our volume limited sample. We find that there are 8486 pairs with angular separation (Equation 2.2) $> 55''$ and 2714 pairs with angular separation $< 55''$. In a similar spirit to the earlier works, we randomly exclude 68.02% pairs with $\theta > 55''$ (Figure 1). After the culling procedure, we are left with a total 5427 pairs in the volume limited sample.

Our volume limited sample contains 75118 galaxies that have no identified pairs according to the criteria applied in subsection 2.2. We term these galaxies as isolated and use them to build our control sample as described in the following subsection.

### 2.4 Building control sample

The physical properties of interacting galaxies should be compared only against the control sample of non-interacting galaxies to detect the impact of tidal interactions. The colour and SFR of galaxies depends on their stellar mass and environment. So it is crucial to ensure that the distributions of stellar mass and local density for the pairs and control samples are statistically indistinguishable. The colour and the star formation activity of galaxies are also known to depend on the redshift. Besides, the redshift dependent selection effects can not
be eliminated completely even in a volume limited sample. So we also decide to match the redshift distributions of the paired galaxies and control sample of isolated galaxies.

For estimating the local density, we find the distance to the $k^{th}$ nearest neighbour from a galaxy. The $k^{th}$ nearest neighbour density \[ \eta_k = \frac{k - 1}{V(r_k)} \] around a galaxy is defined as

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 $r_k$. We have considered the distance to the $5^{th}$ nearest neighbour from each galaxy by taking $k = 5$ in this work. The local density of galaxies can be underestimated near the survey boundary. We consider only those galaxies for which $r_k < r_b$. Here $r_b$ is the closest distance of the galaxy from the survey boundary. We calculate the local density for all the galaxies in our volume limited sample for which the criterion mentioned earlier is satisfied. We finally get the local density estimates for 8886 paired galaxies and 69308 isolated galaxies in our volume limited sample.

We have 5427 galaxy pairs in our volume limited sample after correcting for the fibre collision effect. We have adopted a strategy similar to Ellison et al. 2008 [40] for building the control sample. We build the control sample of the isolated galaxies by simultaneously matching their stellar mass, local density and redshift. For each paired galaxy, we pick 5 unique isolated galaxies matched in stellar mass, local density and redshift. We match the paired galaxies and their controls to within 0.08 dex in stellar mass, 0.001 in local density and 0.005 in redshift. We also simultaneously ensure that only the isolated galaxies that do not have a companion within $\leq 1$ Mpc can be part of the control sample of non-interacting galaxies. We match every paired galaxy to their controls and then perform a Kolmogorov-Smirnov (KS) test on the stellar mass, local density and redshift distributions (Figure 2). The control samples are accepted only when their stellar mass, local density and redshift distributions are consistent with that for the paired galaxies at a level of at least 30% KS probability (Table 1). This implies that the null hypothesis can not be rejected at $\geq 30\%$ confidence level, and the galaxy pair and control samples are highly likely to be drawn from the same parent distribution. The control matching in stellar mass, local density and redshift eliminate most of the biases that can plague a comparison between the two samples [105]. Any other systematic biases equally affect both the samples and should not be a matter of concern here.

Only the paired galaxies with measurements of stellar mass, local density and redshift can be used for the KS test required in our analysis. Further, the condition that there should be at least 5 control galaxies for each paired galaxy reduces the number of available galaxy pairs. Finally, we have 2011 galaxy pairs that fulfil all these criteria. These 2011 galaxy pairs are formed by a total 3835 galaxies. The control sample of the paired galaxies consists of a total 19175 isolated galaxies.

We define the major pairs that have the stellar mass ratio in the range $1 \leq \frac{M_1}{M_2} < 3$. All the pairs with stellar mass ratio $3 \leq \frac{M_1}{M_2} \leq 10$ are identified as minor pairs. We classify the 2011 galaxy pairs according to this criteria and find that there are 1831 major pairs and 180 minor pairs. We further note that 649 major pairs have a projected separation $r_p = 0$. This can happen if the two members in a pair have a non-zero radial separation but lie along the same line of sight. Such cases may also arise in a merger system where the angular separation between the two members are extremely small. Unreliable deblending can also lead to false identification of single galaxies as close pairs. It is difficult to ascertain the $r_p = 0$ pairs as
mergers based on pair separation alone. So we discard these pairs from our analysis. We also drop the corresponding control galaxies from our control sample. We finally have 1182 major pairs and 180 minor pairs in our volume limited sample, that have measurements of dust corrected colour, SFR and local density.

Figure 3. The top left panel shows the cumulative median SFR for major pairs as a function of the projected separation. The results for all the major pair is shown using the black curve. The $1-\sigma$ error bars shown here are obtained using 10 jackknife samples from the original data. The results for the more massive and less massive members in major pairs are shown separately in the same plot using the green and pink curves, respectively. The $1-\sigma$ error bars for the more massive and less massive members in major pairs are comparable to that shown for all members in major pairs (black curve). We do not show these errorbars here for the sake of clarity. The median SFR for the control samples of each set of galaxies are shown with the horizontal straight lines. The bottom left panel shows the cumulative median SFR as a function of projected separation for the minor pairs. We show the cumulative median $(u-r)$ colour as a function of projected separation for the major and minor pairs in the top right and bottom right panels. The results for the more massive and less massive members of the galaxy pairs are shown together in each of these panels.

3 Results

3.1 Impact of major and minor interactions on star formation rate and colour

We show the cumulative median of the SFR and the dust corrected $(u - r)$ colour of the major pairs as a function of the projected separation respectively in the top left and top right panels of Figure 3. The black curves in these two panels show the results for all the major
Figure 4. Same as Figure 3 but here we show together with the results for the major and minor pairs at high-density and low-density environments.

pairs in our volume limited sample. The $1 - \sigma$ error bars are obtained using 10 jackknife samples prepared from the original data. The horizontal black lines in the top two panels show the respective medians for their control samples. In the top left panel, we find that the cumulative median SFR of the major pairs increases with decreasing pair separation and rises above the control median below $30 \text{ kpc}$. It is interesting to note that the same trend is also observed in the top right panel, where the dust corrected $(u - r)$ colour of the major pairs decreases with decreasing separation and goes below the control median below $30 \text{ kpc}$. An increase in the SFR corresponds to a decrease in the $(u - r)$ colour. So the top two panels together indicate that the tidal interactions in major pairs trigger starburst at closer pair separation. The enhancement is most pronounced at projected separation $< 30 \text{ kpc}$.

It is also interesting to note the presence of a bump in both the top panels. We find that both the cumulative SFR and $(u - r)$ colour show an upturn and a downturn at $70 \text{ kpc}$ where they intersect their control medians. The fact that these curves intersect their control medians at $\sim 30 \text{ kpc}$ and $70 \text{ kpc}$ suggest the presence of a transition region where the tidal interaction can impact the SFR and colour in both directions. The presence of identical features for both the SFR and colour suggest that this can not arise due to statistical fluctuations or chance appearance. We note that such an upturn and downturn in the SFR at $50 \text{ kpc}$ have been already reported by several earlier studies [33, 35, 40]. The number of non-interacting false pairs increase at larger separation due to the projection effects. The presence of the transition region marked by the upturn and downturn is generally ascribed to the contaminations from
the projection effects.

The effect of the tidal interaction diminishes with the increasing pair separation. A gradual change can be seen up to 200 kpc in both the top panels. Both the SFR and the \((u - r)\) colour plateaus out to nearly constant values beyond a separation of 200 kpc. However, as noted earlier, the pairs with wider separation are likely to be contaminated from the projection effects. These pairs may not truly represent either the field population or the truly interacting systems. It can be clearly seen from the deviation of the cumulative medians from the respective control medians even at wider separation.

We also show together with the results for the more massive and less massive members in major pairs in the top panels of Figure 3. Our results indicate that the tidal interactions impart a greater influence on the more massive members in major pairs. We note that the median SFRs in the control samples of the more massive and less massive members in major pairs are nearly identical. This can be attributed to the fact that the heavier and lighter members in major pairs have similar stellar masses that are within a factor of < 3. It also implies that such variations in mass do not cause a noticeable differences in the SFR of the isolated galaxies.

The effects of tidal interactions on the minor pairs in our volume limited sample are shown in the two bottom panels of Figure 3. In the bottom left panel of this figure, we show the cumulative median SFR of the minor pairs as a function of the projected separation. We find that the SFR show a gradual decrease with the decreasing separation, and the SFR in minor pairs are lower than their control median at all separations. These indicate that the tidal interactions in minor pairs suppress the star formation in the intrinsically brighter galaxy pairs. This suppression is contrary to the tidally triggered SFR enhancement in major pairs. The median SFRs in the control samples of the more massive and less massive members in minor pairs are markedly different. This is caused by larger mass differences between the two members in minor pairs. The bottom right panel showing the cumulative \((u - r)\) colour as a function of the pair separation also exhibits the same trend as SFR. We see that the minor pairs become redder with decreasing pair separation. We note that both the more massive and less massive members in minor pairs suppress their star formation and become redder at closer separation. In both the bottom panels of Figure 3, we note that the magnitudes of the deviations from the corresponding control medians are larger for the less massive members in minor pairs. This clearly indicates that the minor interactions influence the SFR and colour of the lighter members in pairs to a greater extent. The minor interactions are usually known to trigger star formation in the low luminosity star forming galaxies. We consider only the brighter galaxies with a relatively lower SFR and redder colour in our sample that can be clearly seen from the median SFR and colour of the major and minor pairs and their controls in different panels of Figure 3. Our results indicate that the minor interactions quench star formation in the intrinsically brighter galaxy pairs.

### 3.2 Environmental dependence of major and minor interactions

We address the environmental dependence of the major and minor interactions in Figure 4. We use the local density at the location of each paired galaxy to characterize their environment. Once the pairs are classified as major and minor, we sort the local densities for each type of galaxy pair and determine the respective median densities. We use the median density as a cut that divides each sample into two subsamples, each comprising an equal number of galaxies. We define the densities above and below the median as high and low, respectively.
Besides the results for the entire sample of major and minor pairs, we also show together with the results for these pairs in high-density and low-density environments in different panels of Figure 4. The black curves in each of the four panels of Figure 4 are the same as those shown in the corresponding panels of Figure 3. In each panel, the results for the paired galaxies in low-density and high-density environments are separately shown using pink and green colours. The top two and the bottom two panels of Figure 4 show the results for the major pairs and minor pairs, respectively. The top left panel of Figure 4 show that the cumulative median SFR for major pairs in the low-density regions is significantly higher than their control median for smaller pair separations. It decreases with the increasing separation but remains above the corresponding control median up to at least 100 kpc. On the other hand, the SFR of the major pairs hosted in the high density regions remains below their control median throughout the entire length scale. This result suggests that the SFR can get suppressed in the major pairs in the high-density regions. The top right panel of Figure 4 show the results for the cumulative median \((u - r)\) colour. We find the same trend with the galaxy colour of major pairs. The major pairs in the low-density regions become bluer with decreasing pair separation, and the colours for these pairs stay below their control median up to 100 kpc. The colour of the major pairs in high-density regions remains above their control median for the entire length scale that indicates that the major pairs in the high-density regions are redder than their isolated controls in similar environments. The results in the top two panels of Figure 4 thus tell us that the major interactions can both trigger starburst or quench star formation depending on their environment. It may be noted that the median SFRs in the control samples of major pairs at the low density and high density regions are different due to the environmental dependence of star formation.

We show the results for the minor pairs in the high-density and low-density environments in the bottom two panels of Figure 4. The bottom left panel shows the cumulative median SFR, and the bottom right panel shows the cumulative median \((u - r)\) colour as a function of the projected separation. We find that all the curves in the bottom left panel stay below their control median, and all the curves in the bottom right panel lie above their control median for the entire range of pair separation. The SFR progressively diminishes, and the colour gradually reddens with the decreasing pair separation at low and high-density regions. These results indicate that the minor interactions in brighter pairs always quench their star formation irrespective of their environments. The bottom two panels also clearly show that quenching in minor pairs is more pronounced in the high-density regions.

4 Conclusions

We study the effects of tidal interactions on star formation rate, and the dust corrected \((u - r)\) colour of paired galaxies using a volume limited sample from the SDSS. We classify the galaxy pairs as ‘major’ and ‘minor’ based on their stellar mass ratio and then study the SFR and colour in these pairs as a function of the projected separation. These results are then compared against those obtained from the control samples of isolated galaxies. We prepare the control samples by matching the redshift, stellar mass and local density of the paired galaxies in our sample. The tidal interactions may not have an equal impact on both the members of a galaxy pair. So we study the effects of the tidal interaction on the properties of the more massive and less massive members in a pair. Further, the environment is known to be an important driver of galaxy evolution. We separately study the impact of major and
minor interactions on SFR and colour in high density and low-density environments. The main conclusions of this analysis are as follows:

(i) We find that the major interactions significantly enhance the SFR in paired galaxies up to at least 30 kpc. The efficiency of the tidally triggered star formation activity diminishes with the increasing pair separation. The tidal interaction seems to influence SFR even at larger length scales. However, this is difficult to confirm due to significant contamination from spurious pairs at wider separations. Besides the SFR, the dust corrected \((u-r)\) colour is strongly affected by the major interactions. The major galaxy pairs become increasingly bluer at smaller projected separations. The interaction induced change in the colour of the major pairs also extends up to 30 kpc. The impact of major interactions on colour shows the same trend as those observed for the SFR. We find that the more massive members in major pairs exhibit a more significant change in SFR and colour.

(ii) The minor interactions in galaxies with higher intrinsic luminosity suppress the SFR in both members in a pair. The suppression of the SFR in minor pairs increases with the decreasing pair separation. The changes are most prominent within 100 kpc but are present throughout the entire length scale probed. The results at larger pair separations are contaminated by the projection effects and are less reliable. The colour of the minor pairs becomes increasingly redder at smaller pair separations. These results together suggest that the minor interactions quench the star formation in intrinsically brighter galaxy pairs. Interestingly, we find that the impact of tidal interactions are more significant in the less massive members of the minor pairs.

(iii) The environment characterized by the local density plays a crucial role in influencing the star formation activity and colour of the galaxy pairs. We find that SFR enhancement due to major interaction becomes more pronounced in the low-density regions. The sample of major pairs in low-density exhibits a marked increase in star formation activity than the undivided sample of major pairs. The enhancement of star formation activity in such pairs extends to a larger length scale up to 100 kpc. Contrary to this, the major pairs in the high-density regions significantly decrease star formation activity at all pair separations. We observe a similar trend with the colour of major pairs in low-density and high-density regions. The major pairs in the low-density environment become increasingly bluer at smaller pair separations when compared with their control samples. The changes in colour in the low-density sample are much more pronounced than its parent sample and extend out to 100 kpc. The major pairs in the high-density regions are significantly redder than their control galaxies at all pair separations. These results indicate that the major interaction between galaxies can enhance or quench star formation depending on their embedding environments.

(iv) The minor interactions between intrinsically brighter galaxies always suppress the star formation irrespective of their environment. We find that the minor pairs at both the low-density and high-density regions are significantly less star forming and redder as compared to their control matched counterparts.

We now compare our results with the earlier studies and discuss the implications of our findings. We observe that a significant enhancement in SFR of paired galaxies within the projected separation of 30 kpc is consistent with most of the previous studies. Several earlier works studied the role of environment on interaction induced SFR enhancement in galaxy pairs. Lambas et al. [33] studied the effects of galaxy interactions in the field using 2dFGRS and find that the SFR for paired galaxies is significantly enhanced compared to the isolated galaxies. They also noted that these enhancements are more significant for the brighter galaxies in a pair. Some other studies [40, 44] analyzed the SDSS galaxies in the low
density regions to reach a similar conclusion. There are observational evidences that SFR in paired galaxies may be influenced by tidal interactions up to 150 kpc [52, 106]. Our results for the major interactions in the low-density environments are consistent with these results. The higher fraction of gas-rich and bulge-less galaxies in the low-density environments favour the greater efficiency of tidally triggered star formation. It has been found that the close passage between bulge-less galaxies are the most efficient in triggering star formation [107]. Alonso et al. [34] studied the effects of galaxy interactions in groups and clusters using the 2dFGRS data and reported that the interaction induced star formation enhancement is less efficient in the high-density regions. Their results show that the galaxy pairs in rich groups are systematically redder than other group members. The dominance of the gas-poor and bulge dominated systems in the high density environments may be the primary reason for the lower efficiency of interaction induced SFR enhancement. It is known that the interaction induced star formation are less efficient in bulge-dominated galaxies as the central bulge provides stability against tidal torques [108].

Interestingly, we observe a quenching of star formation in major pairs at high-density environments. This result is different from the earlier observations and may have several implications. The galaxy interactions in denser environments may have been very efficient in the past, leaving very little gas for new star formation. The galaxies at early stage of their evolution lack stability and consequently the effectiveness of the tidal interaction in inducing star formation is larger during this period [14]. Further, the tidal interactions may also cause gas loss through AGN or shock driven winds [86, 87], induce bar quenching [109] and morphological quenching [110]. It may also be noted that we consider only the intrinsically brighter galaxies in our analysis. The quenching in these pairs in the high density environments indicates that the intrinsic luminosity of the galaxy pairs are also important besides their luminosity or mass ratio. Our results imply that the major interactions can enhance or suppress the star formation in galaxy pairs based on their environments and luminosity. Such interaction induced effects in both directions can contribute to the observed bimodality in colour and other galaxy properties.

The minor interactions are known to trigger a mild enhancement in the star formation activity. Ellison et al. [40] noted that the less luminous galaxies in minor pairs are more susceptible to enhanced star formation. We find that the minor interactions in the intrinsically brighter galaxy pairs quench star formation irrespective of their environment. The more luminous galaxies in the intrinsically brighter pairs have higher stellar mass and are generally quiescent galaxies with bulge dominated morphology [111]. The more massive members in these minor pairs may curtail their star formation through mass quenching [112–115]. They can also quench the star formation in their less massive companions by stripping away gas and leading them to starvation. Our analysis shows that the lighter members in minor pairs experience a greater reduction in their star formation. The minor interactions may thus enhance or suppress star formation in galaxy pairs depending on their intrinsic luminosity. Our results suggest that the minor interactions can significantly contribute to the observed bimodality.

We have selected the control galaxies by closely matching the redshift, stellar mass and environment that significantly reduces the biases in our result. However, a few caveats remain in our analysis. All the galaxies in close pairs may not be undergoing interactions. Some of them may be approaching each other and are yet to experience an encounter. There may also be pairs that are undergoing interactions without any SFR enhancement. Further, there are uncertainties in identifying galaxy pairs based on their projected separation and velocity.
difference. Some of the selected pairs may not be close in three dimensions. The chance superposition in the high-density regions like groups and clusters may also produce spurious pairs at both close and wide separations [34].

Finally, we conclude that the galaxy interactions and environment both play significant roles in galaxy evolution. The tidal interactions may or may not trigger starbursts depending on the physical properties of galaxies and their environment. We find that for the intrinsically brighter galaxies, the major interactions enhance the star formation rate in the low-density environments and suppress it in the high density environments. On the other hand, the minor interactions in the intrinsically brighter galaxies always quench star formation irrespective of their environments. It would also be interesting to study the effects of galaxy interactions in different geometric environments of the cosmic web. We plan to carry out such an analysis in future.

ACKNOWLEDGEMENT

The authors thank the SDSS team for making the data publicly available. 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 acknowledges IISER Tirupati for support through a postdoctoral fellowship.

Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the U.S. Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS website is http://www.sdss.org/.

The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions. The Participating Institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, University of Basel, University of Cambridge, Case Western Reserve University, University of Chicago, Drexel University, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Scientist Group, the Chinese Academy of Sciences (LAMOST), Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, Ohio State University, University of Pittsburgh, University of Portsmouth, Princeton University, the United States Naval Observatory, and the University of Washington.

References

[1] M. J. Rees, & J. P. Ostriker, MNRAS, 179, 541 (1977)
[2] J. Silk, ApJ, 211, 638 (1977)
[3] S. D. M. White, & M. J. Rees, MNRAS, 183, 341 (1978)
[4] S. M. Fall, & G. Efstathiou, MNRAS, 193, 189 (1980)
[5] P. Madau, H. C. Ferguson, M. E. Dickinson, M. Giavalisco, C. C. Steidel, & A. Fruchter, MNRAS, 283, 1388 (1996)
[6] E. F. Bell, C. Wolf, K. Meisenheimer, H.-W. Rix, A. Borch, S. Dye, M. Kleinheinrich, et al., ApJ, 608, 752 (2004)
[7] S. M. Faber, C. N. A. Willmer, C. Wolf, D. C. Koo, B. J. Weiner, J. A. Newman, M. Im, et al., ApJ, 665, 265 (2007)
[8] D. C. Martin, T. K. Wyder, D. Schiminovich, T. A. Barlow, K. Forster, P. G. Friedman, P. Morrissey, et al., ApJS, 173, 342 (2007)
[9] C. Ruhland, E. F. Bell, B. Häußler, E. N. Taylor, M. Barden, D. H. McIntosh, ApJ, 695, 1058 (2009)
[10] J. R. Bond, L. Kofman, & D. Pogosyan, Nature, 380, 603 (1996)
[11] A. Toomre, J. Toomre, ApJ, 178, 623 (1972)
[12] J. E. Barnes, L. Hernquist, ApJ, 471, 115 (1996)
[13] J. C. Mihos, L. Hernquist, ApJ, 464, 641 (1996)
[14] P. B. Tissera, R. Domínguez-Tenreiro, C. Scannapieco C., A. Sáiz, MNRAS, 333, 327 (2002)
[15] T. J. Cox, P. Jonsson, J. R. Primack, R. S. Somerville, MNRAS, 373, 1013 (2006)
[16] P. Di Matteo, F. Combes, A.-L. Melchior, B. Semelin, A&A, 468, 61 (2007)
[17] M. Montuori M., P. Di Matteo, M. D. Lehnert, F. Combes, B. Semelin, A&A, 518, A56 (2010)
[18] D. S. N. Rupke, L. J. Kewley, J. E. Barnes, ApJL, 710, L156 (2010)
[19] P. Torrey, T. J. Cox, L. Kewley, L. Hernquist, ApJ, 746, 108 (2012)
[20] F. Renaud, F. Bournaud, K. Kraljic, P.-A. Duc, MNRAS, 442, L33 (2014)
[21] Tissera P. B., ApJ, 534, 636 (2000)
[22] M. J. Perez, P. B. Tissera, D. G. Lambas, C. Scannapieco, A&A, 449, 23 (2006)
[23] C. Lacey, S. Cole, MNRAS, 262, 627 (1993)
[24] O. Fakhouri, C.-P. Ma, MNRAS, 386, 577 (2008)
[25] R. S. Somerville, J. R. Primack, S. M. Faber, MNRAS, 320, 504 (2001)
[26] Q. Guo, S. D. M. White, MNRAS, 384, 2 (2008)
[27] E. F. Bell, D. B. Zucker, V. Belokurov, S. Sharma, K. V. Johnston, J. S. Bullock, D. W. Hogg, et al., ApJ, 680, 295 2008
[28] J. C. Mihos, L. Hernquist, ApJL, 425, L13 (1994)
[29] C. Mastropietro, B. Moore, L. Mayer, J. Wadsley, J. Stadel, MNRAS, 363, 509 (2005)
[30] T. J. Cox, P. Jonsson, R. S. Somerville, J. R. Primack, A. Dekel, MNRAS, 384, 386 (2008)
[31] R. B. Larson, B. M. Tinsley, ApJ, 219, 46 (1978)
[32] E. J. Barton, M. J. Geller, S. J. Kenyon, ApJ, 530, 660 (2000)
[33] D. G. Lambas, P. B. Tissera, M. S. Alonso, G. Coldwell, MNRAS, 346, 1189 (2003)
[34] M. S. Alonso, P. B. Tissera, G. Coldwell, D. G. Lambas, MNRAS, 352, 1081 (2004)
[35] B. Nikolic, H. Cullen, P. Alexander, MNRAS, 355, 874 (2004)
[36] M. S. Alonso, D. G. Lambas, P. Tissera, G. Coldwell, MNRAS, 367, 1029 (2006)
[37] D. F. Woods, M. J. Geller, E. J. Barton, AJ, 132, 197 (2006)
[38] D. F. Woods, M. J. Geller, AJ, 134, 527 (2007)
[39] E. J. Barton, J. A. Arnold, A. R. Zentner, J. S. Bullock, R. H. Wechsler, ApJ, 671, 1538 (2007)
[40] S. L. Ellison, D. R. Patton, L. Simard, A. W. McConnachie, 2008, AJ, 135, 1877 (2008)
[41] A. Heiderman, S. Jogee, I. Marinova, E. van Kampen, M. Barden, C. Y. Peng, C. Heymans, et al., ApJ, 705, 1433 (2009)
[42] J. H. Knapen, P. A. James, ApJ, 698, 1437 (2009)
[43] A. R. Robaina, E. F. Bell, R. E. Skelton, D. H. McIntosh, R. S. Somerville, X. Zheng, H.-W. Rix, et al., ApJ, 704, 324 (2009)
[44] S. L. Ellison, D. R. Patton, L. Simard, A. W. McConnachie, I. K. Baldry, J. T. Mendel, MNRAS, 407, 1514 (2010)
[45] D. F. Woods, M. J. Geller, M. J. Kurtz, E. Westra, D. G. Fabricant, I. Dell’Antonio, AJ, 139, 1857 (2010)
[46] D. R. Patton, S. L. Ellison, L. Simard, A. W. McConnachie, J. T. Mendel, MNRAS, 412, 591 (2011)
[47] R. S. Somerville, & J. R. Primack, MNRAS, 310, 1087 (1999)
[48] G. Kauffmann, J. M. Colberg, A. Diaferio, S. D. M. White, MNRAS, 303, 188 (1999)
[49] G. Kauffmann, J. M. Colberg, A. Diaferio, S. D. M. White, MNRAS, 307, 529 (1999)
[50] A. Diaferio, G. Kauffmann, J. M. Colberg, S. D. M. White, MNRAS, 307, 537 (1999)
[51] C. Li, G. Kauffmann, T. M. Heckman, S. D. M. White, Y. P. Jing, MNRAS, 385, 1915 (2008)
[52] J. M. Scudder, S. L. Ellison, P. Torrey, D. R. Patton, J. T. Mendel, MNRAS, 426, 549 (2012)
[53] S. Kaviraj, K.-M. Tan, R. S. Ellis, J. Silk, MNRAS, 411, 2148 (2011)
[54] D. G. Lambas, S. Alonso, V. Mesa, A. L. O’Mill, A&A, 539, A45 (2012)
[55] A. Oemler, ApJ, 194, 1 (1974)
[56] M. Davis, & M. J. Geller, ApJ, 208, 13 (1976)
[57] A. Dressler, ApJ, 236, 351 (1980)
[58] L. Guzzo, M. A. Strauss, K. B. Fisher, R. Giovanelli, & M.P. Haynes, ApJ, 489, 37 (1997)
[59] I. Zehavi, et al. 2002, ApJ, 571, 172 (2002)
[60] D. W. Hogg, et al., ApJ Letters, 585, L5 (2003)
[61] M. R. Blanton, et al., ApJ, 594, 186 (2003)
[62] J. Einasto, G. Hütsi, M. Einasto, E. Saar, D. L. Tucker, V. Müller, P. Heinämäki, & S. S. Allam, A&A, 405, 425 (2003)
[63] T. Goto, C. Yamauchi, Y. Fujita, S. Okamura, M. Seikiguchi, I. Smail, M. Bernardi, & P.L. Gomez, MNRAS, 346, 601 (2003)
[64] G. Kauffmann, S. D. M. White, T. M. Heckman, et al., MNRAS, 353, 713 (2004)
[65] B. Pandey, & S. Bharadwaj, MNRAS, 372, 827 (2006)
[66] C. Park, Y.-Y. Choi, M. S. Vogeley, J. R. Gott, M. R. Blanton, SDSS Collaboration, ApJ, 658, 898 (2007)
[67] M. Mouhcine, I. K. Baldry, & S. P. Bamford, MNRAS, 382, 801 (2007)
[68] B. Pandey, & S. Bharadwaj, MNRAS, 387, 767 (2008)
[69] S. C. Porter, S. Raychaudhury, K. A. Pimbblet, M. J. Drinkwater, MNRAS, 388, 1152 (2008)
[70] S. P. Bamford, R. C. Nichol, I. K. Baldry, et al., MNRAS, 393, 1324 (2009)
[71] M. C. Cooper, A. Gallazzi, J. A. Newman, R. Yan, MNRAS, 402, 1942 (2010)
[72] Y. Koyama, I. Smail, J. Kurk, et al., MNRAS, 434, 423 (2013)
[102] R. De Propris, C. J. Conselice, J. Liske, S. P. Driver, D. R. Patton, A. W. Graham, P. D. Allen, ApJ, 666, 212 (2007)
[103] D. R. Patton, J. E. Atfield, ApJ, 685, 235 (2008)
[104] S. Casertano, & P. Hut, ApJ, 298, 80 (1985)
[105] J. Perez, P. Tissera, J. Blaizot, MNRAS, 397, 748 (2009)
[106] D. R. Patton, P. Torrey, S. L. Ellison, J. T. Mendel, J. M. Scudder, MNRAS, 433, L59 (2013)
[107] T. J. Cox, ASPC, 419, 235 (2009)
[108] J. Binney, S. Tremaine, Galactic Dynamics, Princeton University Press (1987)
[109] M. Haywood, M. D. Lehnert, P. Di Matteo, O. Snaith, M. Schultheis, D. Katz, & A. Gómez, A&A, 589, A66 (2016)
[110] M. Martig, F. Bournaud, R. Teyssier, & A. Dekel, ApJ, 707, 250 (2009)
[111] G. Kauffmann, T. M. Heckman, S. D. M. White, S. Charlot, C. Tremonti, E. W. Peng, M. Seibert, et al., MNRAS, 341, 54 (2003)
[112] J. Binney, MNRAS, 347, 1093 (2004)
[113] Y. Birnboim, & A. Dekel, MNRAS, 345, 349 (2003)
[114] A. Dekel, & Y. Birnboim, MNRAS, 368, 2 (2006)
[115] A. Das, B. Pandey, S. Sarkar, JCAP, 06, 045 (2021)