Bar rejuvenation in S0 galaxies?

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ABSTRACT
Based on the colour measurements from a multi-band, multi-component 2D decomposition’s of S0 and spiral galaxies using SDSS images, we found that bars are bluer in S0 galaxies compared to the spiral galaxies. Most of the S0s in our sample have stellar masses ∼ L∗ galaxies. The environment might have played an important role as most of the S0s with bluer bars are in the intermediate-density environment. The possibility of minor mergers and tidal interactions which occurs frequently in the intermediate-density environment might have caused either a bar to form and/or induce star formation in the barred region of S0 galaxies. The underlying discs show the usual behaviour being redder in S0s compared to spiral galaxies while the bulges are red and old for both S0 and spiral galaxies. The finding of bluer bars in S0 galaxies is a puzzling issue and poses an interesting question at numerical and theoretical studies most of which shows that the bars are long-lived structures with old stellar populations.

Key words: galaxies: bulges — galaxies: evolution — galaxies: formation — galaxies: interactions — galaxies: elliptical and lenticular, cD — galaxies: photometry

1 INTRODUCTION
In the hierarchical structure formation scenario (White & Rees 1978), disc galaxies are believed to have formed via mergers of smaller components. Local disc galaxies are often found to have more than one structural sub-components such as bulges, bars, lenses, rings, see Kormendy & Kennicutt (2004) for a comprehensive review. In fact, more than 60% of disc galaxies that dominate the star formation in the local universe are known to host strong bars (Eskridge et al. 2000; Menéndez-Delmestre et al. 2007; Barazza et al. 2008; Aguerri et al. 2009). Although bars exist at redshift z ∼ 1 – 2, albeit with a lowered frequency (Elmegreen et al. 2004; Jogee et al. 2004; Sheth et al. 2008), it remains unclear when disc galaxies formed their first bar. Some orbital studies and numerical simulations have shown that bars could be destroyed as a result of growing central mass concentration or growing supermassive blackholes or as a result of cold gas inflow to the central region (Pfenniger & Norman 1990; Shen & Sellwood 2004; Hozumi & Hernquist 2005; Bournaud et al. 2005) while some simulations indicate that bars are robust and once formed, it is hard to dissolve them (Athanassoula et al. 2005; Kraljic et al. 2012). So in the absence of legitimate evidences and clues, it remains a harder problem to understand whether the same bar continued to exist in the present day-galaxies or it has been dissolved and rejuvenated (Bournaud & Combes 2002).

One of the possible ways to resolve this issue would be to investigate the stellar population in the bar region and compare with the rest of the galaxy. This is a challenging task to accomplish as stars in the bar, bulge and the disc are often mixed and we only see what is along the line of sight. The bar, being one of the strongest non-axisymmetric structure in the disc, plays an active role in the mixing of stars in the galaxy (Fraser-McKelvie et al. 2019). Not only that, it is the driver of gas inflow in the central region and thereby the cause of star formation activity (Aguerri 1999) that is seen in the inner bar region, especially around the inner Lindblad resonance (ILR) in the form of a star-forming ring e.g., in NGC 1097 (Martín et al. 2015; Prieto et al. 2019). Nevertheless, when looked through the infrared, most bars in the local universe to a large extent are composed of a red and old stellar population (Pérez et al. 2009; Sánchez-Blázquez et al. 2011), except probably at the resonance locations (Wozniak 2007). To understand the finer details on the spatial variation of stellar population and star formation histories, one would require high spatial resolution IFU data on a statistically significant sample of disc galaxies. In absence of that, stellar population studies of galaxies beyond the Local Group have been investigated primarily using the broad-band colours. Although in the literature (Barway et al. 2013, & references therein), the observed stellar population has been studied using a galaxy’s global colour,

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stellar population properties are known to vary between the different structural components of a disc galaxy e.g., its bulge, disc or in some cases the bar (Head et al. 2014; Sánchez-Blázquez et al. 2011; Hudson et al. 2010; Simard et al. 2011; Gadotti 2009). The multi-band decomposition of a barred galaxy into bulge, bar and disc would thus allow one to study the distribution of colours for each component and its stellar population properties within limitation. In this paper, we use broad-band colour as a proxy to stellar population to understand the evolutionary aspect of bars by comparing them in spiral and S0 galaxies. The lowered bar frequency in S0 galaxies (Buta et al. 2010a; Nair & Abraham 2010; Barway et al. 2011) might indicate that bars in S0 galaxies are either difficult to form or bars are dissolving (Bournaud & Combes 2002; Bournaud et al. 2005) or bars are weaker to be detected compared to normal barred spiral galaxies. Whatever it might be, if these bars survive since their formation, one would expect them to be redder in colour in present-day galaxies. The same might hold true if a barred spiral galaxy transforms to a barred S0 as a result of a number of physical processes such as ram pressure stripping of gas and dust (Gunn & Gott 1972; Larson et al. 1980); galaxy harassment (Moore et al. 1996) or gas starvation leading to star-formation shut down (Bekki et al. 2002; Peng et al. 2015) or even mergers as shown by numerical simulations (see Bekki & Couch 2011; Eliche-Moral et al. 2013; Tapia et al. 2014; Querejeta et al. 2015). So naively one would expect to find bars colours in S0s to be comparatively redder or similar to that in barred spirals. In this paper, we report, contrary to general understanding, that some bars are bluer in S0s compared to spirals and discuss its implications.

The paper is organized as follows. Section 2 describes the sample that we used for this work. We present our results in section 3, section 4 and section 5. Section 6 is devoted to discussion and conclusions. Throughout this paper, we use the standard concordance cosmology with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ and $h_{100} = 0.7$.

2 SAMPLE AND ANALYSIS

For this work, we use the data from Kruk et al. (2018) (hereafter K18) which present the multi-band 2D photometric decomposition of ~3500 galaxies from SDSS with strong bars. Details on data and methods can be found in K18. Here we provide a summary for the benefit of readers. K18 uses publicly available images from SDSS in all the five bands $u$, $g$, $r$, $i$ and $z$ for 2D photometric decomposition with the bulge, disc and bar components using GALFITM. This code was developed by the MegaMorph project (Bamford et al. 2011; Häusler et al. 2013) and is a modified version of GALFIT 3.0 (Peng et al. 2010). The advantage of using GALFITM is simultaneously fitting the wavelength-dependent model with multiple components to SDSS images in five bands. During the fitting user can vary the parameters between the bands and/or fixing some of them. The simultaneously fitting in SDSS five bands increases the overall signal-to-noise ratio (S/N). It also uses the colour differences between the components to help with the decomposition which provides consistent colours for each component. During the fitting, K18 constrain some of the parameters, however, the magnitude in each band was allowed to vary which help to ignore colour and, hence stellar population gradients within the independent models of each component.

Using an iterative process, K18 fitted the barred galaxies in the sample with three components (disc+bar+bulge) for bulge dominated galaxies and two components (disc+bar) for disc dominated galaxies by adding one component at a time. The Sersic profiles were used to fit the bulge and bar components while the disc was fitted with the exponential profile. This gives magnitudes, effective radii and Sersic index for bulge and bar, magnitudes, scale lengths for the disc in each band. The magnitudes in $g$ and $i$ bands were used to obtain colours for bulge, bar and disc.

The uncertainties on the output parameters computed by GALFITM is statistical due to its assumption of the source of error is Poisson noise and are known to underestimate the real error. It does not take into account the errors in sky estimations, the accuracy of PSF and correlated noise due to parameter degeneracy. As shown by Peng et al. (2010), the uncertainties in estimating the sky background are one of the main source of errors. By obtaining the uncertainties in sky estimation for single Sersic fitting using GALFITM, Vika et al. (2013) showed that the uncertainty in $g$ band magnitude is ±0.09 and in $i$ band magnitude is ±0.11, an indicative uncertainty value for K18 measurements as they use the same software and images of the same quality. Please note the uncertainties on fitting multiple components are more complex and not trivial to estimate. For detailed discussion on this subject, we recommend reader to refer K18 and Vika et al. (2013).

Dust reddening, extinction and K-corrections were applied to the magnitudes and colours. As mentioned in K18, the effect of internal dust reddening is not significant as galaxies in the sample is moderately face-on (i ≤ 60°). We have used 2D decomposition parameters in $g$, $r$, $i$ and $z$ bands as these are more reliable compared to decomposition in $u$ and $z$ band. These parameters for bulge dominated galaxies are used to explore the colour distribution of bars, bulges and discs of sample galaxies as a function of galaxy morphology. The differences in component colours and trends with stellar mass and environment will be useful to investigate the bar properties, particularly in S0 galaxies.

Next, we search for reliable visual morphological classification for galaxies in K18 to have a sample of S0 and spiral galaxies, respectively. For this purpose, we cross-match K18 sample of barred galaxies with Nair & Abraham (2010) catalogue which provides a careful morphological classification using SDSS images in all the five bands $u$, $g$, $r$, $i$, $z$. This catalogue can differentiate between S0 galaxies into S0-, S0, and S0/a and spirals galaxies into Sa, Sb, Sbc, Sc, Scd, Sdm, Sm, and Im. The galaxies in Nair & Abraham (2010) catalogue have been classified twice and have estimated a mean deviation of less than 0.5 T-types. In this work, we group together all types of S0 galaxies (S0-, S0, and S0/a) and refer them as S0s. We do the same to have a spiral galaxy sample.

This cross-match gives 692 galaxies with bulge, disc and bar parameters. We find that out of 692, the number of S0 and spiral galaxies are 211 and 481, respectively. In this spiral galaxy sample, there are 428 early-type spiral galaxies (ranging from Sa-Sbc types) and 53 late-type spiral galaxies.
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3 BULGE, DISC AND BAR COLOUR DISTRIBUTION

Kruk et al. (2018) have shown using $(g-i)$ colour distribution for bulge, disc and bar that the discs are bluer than the bars.
and bulges while there is little difference between the bar and bulge \((g - i)\) colour. The median difference between bulges and discs for \((g - i)\) is 0.33 and between the bars and discs is 0.20. The authors used \((g - i)\) colour as these two bands are sufficiently separated in wavelengths and less affected by dust extinction.

We show the distribution of optical colours \((g - i)\) for the bulge, disc and bar components in Fig. 1 as a function of morphology for S0 and spiral galaxies. While the bulge colour shows no difference, discs in S0 galaxies are redder compared to spiral galaxies with median \((g - i)\) colour difference of 0.15 magnitudes. The bluer discs in spiral galaxies are as per norm (Bakos et al. 2008; MacArthur et al. 2009); however, the distribution of the bar colours in S0s and spiral galaxies are unexpected (Tully et al. 1982; Buta et al. 2010b; Lansbury et al. 2014). Bars in the current sample of S0 galaxies are bluer compared to spiral galaxies with a median \((g - i)\) colour difference of 0.11 magnitude. However, is the difference between bar colours for S0 and spiral galaxies significant? To address this, we perform a statistical test. A commonly used non-parametric test is the Kolmogorov–Smirnov test (hereafter K–S test), which measures the maximum distance \((d)\) between the two cumulative distributions. Under the null hypothesis that the two samples tested are drawn from the same population, a larger maximum distance is less likely to occur. The K–S test reveals that the \((g - i)\) colour distribution for S0 and spiral is drawn from the same distribution is rejected \((d = 0.40)\) with a significance level \((P)\) of \(10^{-5}\) or better.

If we consider a scenario in which a barred S0 galaxy is transformed from a barred spiral galaxy by the mechanisms involving no past major interaction that does not destroy the bar, the stellar content of S0 bars should be dominated by old stars. As a result, one would expect the bar colour to be redder in S0 galaxies compare to those in spirals. However, Fig. 1 reveals an opposite picture. When we compare the \((g - i)\) colour distribution of the bulge, disc and bar components for S0 as an individual morphology class, we see that the discs and bars are bluer compared to bulges; with discs being marginally bluer than bars. On the other hand, for spiral galaxies, the \((g - i)\) colour distributions for the bulges and bars are similar and discs are bluer as one would expect normally (Bakos et al. 2008; MacArthur et al. 2009). In other words, barred spiral galaxies have an older stellar population in the bar and bulge (Sanchez-Blazquez et al. 2011). This brings out a puzzling issue in which bars are bluer and probably star-forming in S0 galaxies - something that is contrary to our overall understanding of galaxy dynamics and evolution (Sellwood 2014; Conselice 2014).

The right panel of Fig. 1 shows the distribution of the effective radii of bulge, bar and disc of S0 (in red) and spiral (in blue) galaxies. The bulge effective radii for S0s and spiral galaxies span a similar range while the bar, as well as disc effective radii, are smaller in S0s compared to spirals. This suggests that our S0 galaxies have smaller bars compare to their spiral counterpart. A two-sample K–S analysis reveals that the distribution of bar and disc effective radii for S0 and spiral is drawn from the same distribution is rejected \((d = 0.36)\) with a significance level \((P)\) of \(10^{-5}\) or better. Note that in the current sample of S0 and spiral galaxies, bulges are, in general, smaller and compact compared to bars whereas discs are bigger.

### 3.1 Role of bulge and disc on bar properties

It will be interesting to consider the role of a bulge and disc to understand comparatively bluer colours of bars in S0 galaxies. Lets first explore the role of discs in bar formation. A number of simulations have shown that the massive, cool, self-gravitating discs are prone to bar instability which leads to the formation of strong bars (Combes & Sanders 1981; Sellwood & Wilkinson 1993; Athanassoula 2002; Dubinski et al. 2009; Saha & Elmegreen 2016) whereas lower mass, comparatively hotter galaxies do not form strong bars, and the bar develops over a longer period of time (Saha et al. 2010; Sheth et al. 2012; Saha 2014). On the observational side, it has been shown that the incidence of a bar in S0 galaxies does not depend on the stellar mass of the host discs (Barway et al. 2016). The \((g - i)\) colour of the disc for S0 is redder compare to spiral galaxies and also the disc effective radii are smaller in S0s compared to spiral galaxies. This shows the possible evidence of secular evolution via bars, quenching of star formation in the discs and possible route to the formation of pseudobulges (Kormendy & Kennicutt 2004).

As shown in K18, the dominant fraction of bulges in these galaxies are of pseudobulge type as found in other studies (Jogee et al. 2005; Kormendy 2013). There are a very few elliptical-like classical bulges in this sample. K18 has used Sersic index ‘n’ for identifying bulges in which bulges with \(n \leq 2\) are classified as pseudobulges and with \(n > 2\) are classified as classical bulges (Fisher & Drory 2008). This identification scheme is still a matter for debate in the literature (Gadotti 2009; Vaghmare et al. 2013); although, for a large sample, researchers generally use it. In this work, we make use of this division for comparing our results with K18 and with different studies in the literature. This division gives us 200 (95 %) pseudo bulges in S0s and 453 (94 %)
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Figure 4. The normalised $(g - i)$ colour distribution for bulge (left), for bar (middle) and for disc (right) plotted as a function of total galaxy mass for S0 (in red) and for spiral (in blue) galaxies. We have used the $10^{10.25} \, M_\odot$ as a mass division similar to K18 (see text for details).

Figure 5. Dependence of specific star formation rate on stellar mass for S0 (left panel) and for spiral (right panel) galaxies as a function of bar colour for massive galaxies ($M_\ast > 10^{10.25} \, M_\odot$). The region between the horizontal blue dashed lines defines the green valley from Salim (2014). Galaxies above the upper blue line ($\log \, sSFR = -10.8$) are termed star forming, and those lying under the lower green line ($\log \, sSFR = -11.8$) are termed quenched galaxies. The grey background density of galaxies is from Bait et al. (2017) which is available publicly for all morphological classes. The S0 galaxy SDSS J123553.51+054723 having bluest bar (shown as blue dot) is at boundary of green valley towards quenched side (left panel).

pseudobulges in Spiral galaxies. Rest of the bulges, 11 (5 \%) in S0 and 28 (4 \%) in spiral galaxies are classical bulges. Given that our sample is dominated by pseudobulges, see also Weinzirl et al. (2009); it will be interesting to explore the $(g - i)$ colour distribution as a function of bulge type. The right panel of Fig. 2 shows the normalised $(g - i)$ colour distribution for Sersic index ‘$n$’; top panel shows the distribution for classical bulges while the bottom panel shows the distribution for pseudobulges. It is clear that for both types of bulges, median $(g - i)$ colour for the bar is comparatively bluer in S0s than in spirals. Amongst the S0 galaxies, the median $(g - i)$ colour of the bar in classical bulges is bluer than for the bar in pseudobulges. It is worth to note that the bluest and reddest bar colour for our sample of S0 galaxies host a classical bulge.

As mentioned earlier, the bulges of barred galaxies for both S0 and spiral galaxies are predominantly of pseudobulge type and are a likely result of the secular evolution processes. The classical bulges, which are believed to have formed by major and minor merger events (Aguerri et al. 2001; Hopkins et al. 2010) are uncommon in our sample of S0 and spiral galaxies and have bluer bars particularly in S0 galaxies. It remains intriguing to explore what make bars bluer in S0 galaxies hosting classical bulges.
Since this sample consists of strongly barred galaxies, it is imperative to examine the bar prominence to understand the bar colour difference we see in S0s and spirals. We use bar-to-total luminosity ratio (Bar/T) to indicate the bar strength or the mass of a bar (see also Weinzirl et al. 2009). Kruk et al. (2018) measured the Bar/T ratio for their sample of galaxies in all five bands of SDSS with a median value of $\sim 0.14$ in $i$-band for bulge dominated galaxies. The right panel of Fig. 2 shows the $(g-i)$ colour distribution for the bar as a function of Bar/T ratio. We use $\text{Bar}/\text{T} = 0.15$ to divide our sample into strong bars and less-strong bars for S0 and spiral galaxies. For $\text{Bar}/\text{T} > 0.15$ i.e., massive bars, there is no difference in bar colour for S0 and spiral galaxies suggesting of having a similar stellar population for the stronger bar in both morphological types. The bar colour difference is more prominent for $\text{Bar}/\text{T} \leq 0.15$ (according to K-S test; $d=0.60$ with a significance level $(P)$ of $10^{-5}$ or better) implying that the less-strong and probably smaller-sized bars are bluer in S0s compared to spiral galaxies. Now, it remains to be investigated what makes smaller bars appear bluer in S0s.

3.2 Role of stellar mass

Dependence of galaxy properties such as size, colour, star formation rate on stellar mass is well known (Conselice 2006). K18 has explored this mass dependence for their sample which contain the galaxies of stellar masses from $10^{9} M_{\odot}$ to $10^{11.5} M_{\odot}$. They have shown that the colours of the discs and bars for low-mass galaxies are bluer compared to massive galaxies when using $10^{10.25} M_{\odot}$ as mass division.

For massive galaxies ($M_{*} > 10^{10.25} M_{\odot}$), the bulge is redder and bulge and bar colours are similar suggesting old stellar populations in both components as can be seen in simulated galaxies from cosmological hydrodynamical simulations (Scannapieco et al. 2010). We are using a sub-sample from K18 obtained by morphological classification in S0 and spiral galaxies and investigate the stellar mass dependence in Fig. 3 which shows the stellar mass distribution for S0 and spiral galaxies. For high and low mass, both morphological classes have a similar span of stellar masses despite having different sample size for S0 and spiral galaxies. Using the same mass division given in K18, we plot the normalised distribution of $(g-i)$ colour for the bulge (left panel), disc (right panel) and bar (middle panel) components in Fig. 4. Interestingly, the bars in massive S0 galaxies are bluer compared to massive spiral galaxies (according to K-S test; $d=0.39$ with a significance level $(P)$ of $10^{-5}$ or better). The scenario is the same for the low mass S0 galaxies in that bars are bluer compared to their spiral counterpart. Interestingly, if we consider only the S0 galaxies in our sample, massive S0 galaxies have the bluer bar colour compare to less massive S0 galaxies (according to K-S test; $d=0.36$ with a significance level $(P)$ of $10^{-5}$ or better). Also, most of the classical bulges hosting S0 galaxies are massive. This indicates that the stellar population of bars in massive S0 galaxies is younger than the spiral galaxies of similar mass range and less massive S0 galaxies.

The $(g-i)$ colour using this mass division for bulge (left panel) and the disc (right panel) is shown in Fig. 4. The disc colours show the expected behaviour i.e. spiral discs are bluer than S0 discs, however, this difference is more pronounced for low mass galaxies. We do not see a difference for the bulge $(g-i)$ colour for the massive S0 and spiral galaxies. For both morphological types, the bulge colour is redder than the bar colour. This probably implies that the bulge does not play a role in turning the bar appear bluer. Though the bulge $(g-i)$ colour for low mass galaxies is bluer compared to bar colour and this difference is more prominent for low mass spiral galaxies.

It is worth to mention here that when the mass division given in K18 is used, the sample size of our galaxies towards the low mass end is considerably less ($\sim 8\%$). The morphological type for most of these low mass spiral galaxies is late-type (Sc and later). This explains the difference between $(g-i)$ colour for the bulge, bar and disc of low mass galaxies for spiral and S0s. The discs of low mass late-type spiral galaxies are gas-rich and hence star-forming (Kennicutt 1983; Zhang et al. 2018). The bulges of low mass late-type spiral galaxies are bluer than S0 again showing typical behaviour. However, the $(g-i)$ colour of the bar is redder for low mass late-type spiral galaxies compared to S0s. This kind of behaviour is only possible when a galaxy is formed through a secular process in which the discs were formed first and bulges emerged from the disc through the gas transported by the bar and likely to be significant in late-type spiral galaxies (Kormendy & Kennicutt 2004).

4 BARRIED GALAXIES ON SSFR-M, PLANE

It will be interesting to investigate the position of our sample of barred galaxies on the sSFR-M$_{\ast}$ plane for massive galaxies ($M_{\ast} > 10^{10.25} M_{\odot}$) as these galaxies are dominant in our sample. Bait et al. (2017) has found using a sample of massive galaxies ($M_{\ast} > 10^{10} M_{\odot}$) that the green valley is mostly populated by early-type spiral and S0 galaxies. These authors suggest that morphology plays an important role in determining the star-forming state of massive galaxies in the local universe; although, they do not consider the role of features like bars and rings. Recently Kelvin et al. (2018) find a significant fraction of rings and lenses in disc-type galaxies in the green valley with a presence of the bar common in most of these galaxies. K18 has shown that the barred disc galaxies are more common in green valley and quenched sequence compared to unbarred galaxies at a given mass. We explore the same by dividing our sample of massive barred disc galaxies into S0s and spiral galaxies on the sSFR-M$_{\ast}$ plane as a function of bar colour with the galaxies common with publicly available data from Bait et al. (2017). These authors used multi-wavelength photometry, from UV-optical-near-mid IR, for $\sim 6000$ galaxies in the Local Universe to model the Spectral Energy Distribution (SED) to estimate the stellar mass and SFRs. Only optical imaging data from the SDSS in $u,g,r,i,z$ bands for all our sample galaxies can be used for SED fitting; however, the UV and Mid-IR data provides a better constraint on recent star formation and dust estimation during SED fitting. Bait et al. (2017) have used aperture matched total magnitudes in UV-optical-IR bands to model the SED, using the publicly available Multi-wavelength Analysis of Galaxy Physical Properties (MAGPHYS) code (da Cunha et al. 2008) to estimate the stellar mass ($M_{\ast}$) and SFRs with typical uncertainty in log $M_{\ast}$ is about 0.048 dex and in log sSFR is about 0.125 dex.

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The disc of spiral galaxies (Gunn & Gott 1972; Moore et al. 2001) scenario where S0 galaxies are formed via stripping gas from blue bar are mostly in Star-forming region. If we consider a bar. We have also noticed that the spiral galaxies with the green valley along with few more S0 galaxies with a blue bar (shown as a blue dot) is at the boundary of the green valley towards the quenched side (left panel).

The S0 galaxy SDSS J123553.51+054723 having the bluest bar (shown as a blue dot) is at the boundary of the green valley along with few more S0 galaxies with a blue bar. Moreover, the bar background density of galaxies is from Bait et al. (2017) which is available publicly for all morphological classes.

Note that in the Fig. 5, the number of spiral galaxies in the AAB star-forming main-sequence is much higher than the S0 galaxies as spiral galaxies are almost double in the number than S0 galaxies. Also as shown in Table 3 of Bait et al. (2017), the fraction of spiral galaxies in star-forming main-sequence is large compared to S0 galaxies. The S0 galaxy SDSS J123553.51+054723 having the bluest bar (shown as a blue dot) is at the boundary of the green valley towards the quenched side (left panel).

It is clear from Fig. 5, spiral galaxies in our sample populate all the region of the plane with the presence of reddest barred spiral galaxies are in the green region. However, S0 galaxies in which most of the bars are bluer compared to spiral galaxies in this sample are in the quenched region and green valley. The bluest barred S0 galaxy SDSS J123553.51+054723 (see Section 5 for more details.) is in the green valley along with few more S0 galaxies with a blue bar. We have also noticed that the spiral galaxies with the blue bar are mostly in Star-forming region. If we consider a scenario where S0 galaxies are formed via stripping gas from the disc of spiral galaxies (Gunn & Gott 1972; Moore et al. 1996) given that the bulges of both types of galaxies are old, a burst of star formation in a bar can move S0 galaxies from quenched region to green valley. It will be interesting to investigate further what could have caused such a burst of star formation in the bar given that the SSP models with an instantaneous burst of star formation 8 Gyr ago could produce (g - i) colour of 1.13 (Fernández Lorenzo et al. 2014) which is close to the median colour of the bar in our S0 galaxy sample. The results presented in the section provide us a clue on bar evolution in massive S0 galaxies where most of the bars are shorter and comparatively bluer than spiral galaxies.

5 BLUEST S0 BAR

In this study, we found that a galaxy SDSS J123553.51+054723.5 hosting one of the bluest bar in our S0 galaxy sample with bar (g - i) colour of 0.40, while bulge which is a classical bulge has (g - i) colour of 1.05 and disc (g - i) colour is 0.95. This galaxy is at redshift 0.042 and has an extended disturbed disc along with the tail (see Fig. 7), a sign of past interaction, possibly with a nearby elliptical galaxy SDSS J123553.79+054539.8 at the same redshift. The HI gas was detected for SDSS J123553.51+054723.5 in the extended GALEX Arecibo SDSS Survey (xGASS) (Catinella et al. 2010) which gives the integrated HI mass log(M_HI/M_⊙) = 8.86. Considering the stellar mass of this galaxy, this implies 0.02. Although compared to normal spiral galaxies the gas to stellar mass ratio is significantly lower, the galaxy is not literally devoid of gas as in many massive S0 galaxies. Since the galaxy seems to be interacting with the neighbour or it could be even in flybys, it might be responsible in triggering star-formation in the central region of this S0 galaxy and might even have led to the formation of the bar (Lokas 2018). Since the galaxy’s stellar mass is 4 × 10^10 M_⊙, it remains unclear whether the central star-formation was due to the accretion of fresh gas (Dekel & Birnboim 2006). Other possibility might be that the interaction or the flyby could excite a bar in the central region as well as ignite star-formation from the residual gas.

6 DISCUSSION AND CONCLUSIONS

While bar formation is discussed in detail in the literature (Saha & Naab 2013), the fate of bars is still unclear in terms of observational evidences. Barred S0 galaxies can be an ideal case to study the fate of bars in the scenario where S0s are thought to have transformed from spiral galaxies via a number of processes such as ram pressure stripping. Some numerical simulations have shown that a bar may be destroyed or weakened by strong gas inflow (Bournaud et al. 2005) while some others have shown that it can survive for a long time (Athanassoula 2005).

Most of S0 galaxies in our sample have small or weak bars. One possibility is that a weak or small bar may dissolve into a lens feature as proposed (Kormendy 1979; Kruk et al. 2018) which interestingly also found that the (g - i) colour for the lenses is bluer compared to bars. Moreover, the bar and lens fraction in S0 galaxies are similar as given in Nair & Abraham (2010) indicate the possibility of bars can dissolve into lenses for S0 galaxies.
Using Hα data, star formation in the bar region for spiral galaxies have been reported in the literature (Martin & Friedli 1997; Sheth et al. 2002). Simulations have been shown that at the edge of the bar region conditions might be favourable for the formation of molecular complexes and thus mini-starbursts (Renaud et al. 2015), however, also for spiral galaxies. There is no such investigation have been done to study star formation in bar region of S0 galaxies. This might be due to the fact that most of the S0 galaxies host small or weak bar. However, star formation can be triggered by a weaker shock due to some interaction when a galaxy is a part of a group or cluster. Barway et al. (2011) have shown that a significant number of barred S0 galaxies are part of a group/cluster environment. For this sample of barred S0 galaxies, we use local environmental density (log $\Sigma$ (Mpc$^{-2}$)) as given in Nair & Abraham (2010). We split our sample of S0 galaxies into low density (log $\Sigma$ (Mpc$^{-2}$) < -0.5), intermediate-density (-0.5 < log $\Sigma$ (Mpc$^{-2}$) < 0.5), and high densities (log $\Sigma$ (Mpc$^{-2}$) > 0.5) similar to Bait et al. (2017).

A distribution of $(g-i)$ bar colour as a function of local environmental density (log $\Sigma$ (Mpc$^{-2}$)) is shown in Fig. 6 indicating that a significant fraction of barred S0 galaxies is in the intermediate-density environment. The median $(g-i)$ colour difference 0.14 magnitudes for bars in S0 galaxies are bluer compared to spiral galaxies in the intermediate-density environment (according to K-S test; d=0.45 with a significance level (P) of 10$^{-3}$ or better). Though the bars in S0 galaxies are bluer compared to spiral galaxies in low- and the high-density environment as well the difference is larger for the intermediate-density environment.

Our findings give rise to an interesting possibility. Does the intermediate-density environment is causing the bar formation in S0 galaxies? If this is the case then these bars should have bluer colour and hence younger compare to spiral galaxies. The possibilities of minor mergers and tidal interactions are more in the intermediate-density environment which can form bars in S0 galaxies as shown in some numerical simulations and have been found observationally (Debattista et al. 2002; Yang et al. 2009; Peirani et al. 2009). At the same time, intermediate-density environment might lead to rejuvenation of star formation, particularly in bar region by facilitating the accretion of fresh gas from gas-rich satellites as suggested by HI observations (Marino et al. 2011).

To summarise, we show that bars with blue colour are common in S0 galaxies compared to that in spiral galaxies. However, what makes these bars bluer is puzzling given that they are smaller in size and their bulges are old. Many of our barred S0 galaxies with bluer bar are in the intermediate-density environment, a possibility of a minor interaction is more and as stated earlier the bar formation can be triggered due to minor interactions. More theoretical and simulation studies are required to explore the fate of the bars in S0 galaxies which can be the ideal laboratories for this inves-

**Figure 7.** $r$ band images of S0 galaxy SDSS J123553.51+054723 having bluest bar. The outermost contour is at $1\sigma = 0.0253$, subsequent inward contours are drawn at $3\sigma$, $10\sigma$, $20\sigma$, $40\sigma$. The S0 disc (SDSS J123553.51+054723, galaxy on the right) showing disturbed morphology and signs of interaction possibly with the companion (left) at a projected separation of 700 kpc. The total counts in the magenta box of length 31.4 kpc is 38.4 which is about 6 times more than the background.
tigation. Spatially resolved stellar populations of bars using IFU surveys such as MaNGA will provide useful insight and this can be the subject of future work.

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REFERENCES

Aguerri J. A. L., 1999, A&A, 351, 43
Aguerri J. A. L., Balcells M., Peletier R. F., 2001, A&A, 367, 428
Aguerri J. A. L., Méndez-Abreu J., Corsini E. M., 2009, A&A, 495, 491
Athanasoula E., 2002, ApJ, 569, L83
Athanasoula E., 2005, MNRAS, 358, 1477
Athanasoula E., Lambert J. C., Dehnen W., 2005, MNRAS, 363, 496
Balt O., Barway S., Wadadekar Y., 2017, MNRAS, 471, 2687
Bakos J., Trujillo I., Pohlen M., 2008, ApJ, 683, L100
Bamford S. P., Hämmerl B., Rojas A., Borch A., 2011, in Evans I. N., Accomazzi A., Mink D. H., eds, Astronomical Society of the Pacific Conference Series Vol. 442, Astronomical Data Analysis Software and Systems XX, p. 479
Barazza F. D., Jogee S., Marinova I., 2008, ApJ, 675, 1194

Barway S., Wadadekar Y., Kembhavi A. K., 2011, MNRAS, 410, L18
Barway S., Wadadekar Y., Vaghmare K., Kembhavi A. K., 2013, MNRAS, 432, 430
Barway S., Saha K., Vaghmare K., Kembhavi A. K., 2016, MNRAS, 463, L41
Bekki K., Couch W. J., 2011, MNRAS, 415, 1783
Bekki K., Couch W. J., Shioya Y., 2002, ApJ, 577, 651
Bournaud F., Combes F., 2002, A&A, 392, 83
Bournaud F., Combes F., Semelin B., 2005, MNRAS, 364, L18
Buta R., Laurikainen E., Salo H., Knapen J. H., 2010a, ApJ, 721, 259
Buta R., Laurikainen E., Salo H., Knapen J. H., 2010b, ApJ, 721, 259
Catinella B., et al., 2010, MNRAS, 403, 683
Combes F., Sanders R. H., 1981, A&A, 96, 164
Conselice C. J., 2006, MNRAS, 373, 1389
Conselice C. J., 2014, ARA&A, 52, 291
Debattista V. P., Corsini E. M., Aguerri J. A. L., 2002, MNRAS, 332, 65
Dekel A., Birnboim Y., 2006, MNRAS, 368, 2
Dubinski J., Berentsen I., Shlosman I., 2009, ApJ, 697, 293
Eliche-Moral M. C., González-García A. C., Aguerri J. A. L., Gallego J., Zamorano J., Balcells M., Prieto M., 2013, A&A, 552, A67
Elmegreen B. G., Elmegreen D. M., Hirst A. C., 2004, ApJ, 612, 191
Eskridge P. B., et al., 2000, AJ, 119, 536
Fernández Lorenzo M., et al., 2014, ApJ, 788, L39
Fisher D. B., Drory N., 2008, AJ, 136, 773
Fraser-McKelvie A., et al., 2019, MNRAS, 488, L6
Gadotti D. A., 2009, MNRAS, 393, 1531
Gunn J. E., Gott III J. R., 1972, ApJ, 176, 1
Häußler B., et al., 2013, MNRAS, 430, 330
Head J. T. C. G., Lucey J. R., Hudson M. J., Smith R. J., 2014, MNRAS, 440, 1690
Hopkins P. F., et al., 2010, ApJ, 715, 292
Houarni S., Herqustein L., 2005, PASJ, 57, 719
Hudson M. J., Stevenson J. B., Smith R. J., Wegner G. A., Lucey J. R., Simard L., 2010, MNRAS, 409, 405
Jogee S., et al., 2004, ApJ, 615, L105
Jogee S., Scoville N., Kenney J. D. P., 2005, ApJ, 630, 837
Kelvin L. S., et al., 2018, MNRAS, 477, 4116
Kennicutt R. C. J., 1983, ApJ, 272, 54
Kormendy J., 1979, ApJ, 227, 714
Kormendy J., 2013, Secular Evolution in Disk Galaxies. p. 1
Kormendy J., Kennicutt Jr. R. C., 2004, ARA&A, 42, 603
Kraljic K., Bournaud F., Martig M., 2012, ApJ, 757, 60
Kruk S. J., et al., 2018, MNRAS, 473, 4731
Lansbury G. B., Lucey J. R., Smith R. J., 2014, MNRAS, 439, 1749
Lawson B. F., Tinsley B. M., Caldwell C. N., 1980, ApJ, 237, 692
Lokas E. L., 2018, ApJ, 857, 6
MacArthur L. A., González J. J., Courteau S., 2009, MNRAS, 395, 28
Marino A., Bianchi L., Rampazzo R., Thilker D. A., Annibali F., Bressan A. r., Buson L. M., 2011, ApJ, 736, 154
Martin P., Friedli D., 1997, A&A, 326, 449
Martín S., et al., 2015, A&A, 573, A116
Menéndez-Delmestre K., Sheth K., Schinnerer E., Jarrett T. H., Scoville N. Z., 2007, ApJ, 657, 790
Moore B., Katz N., Lake G., Dressler A., Oemler A., 1996, Nature, 379, 613
Nair P. B., Abraham R. G., 2010, ApJS, 186, 427
Peirani S., Hammer F., Flores H., Yang Y., Athanassoula E., 2009, A&A, 496, 51
Peng C. Y., Ho L. C., Impey C. D., Rix H.-W., 2010, AJ, 139, 2097

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