Why are classical bulges more common in S0 galaxies than in spiral galaxies?

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ABSTRACT

In this paper, we try to understand why the classical bulge fraction observed in S0 galaxies is significantly higher than that in spiral galaxies. We carry out a comparative study of the bulge and global properties of a sample of spiral and S0 galaxies in a fixed environment. Our sample is flux limited and contains 262 spiral and 155 S0 galaxies drawn from the Sloan Digital Sky Survey. We have classified bulges into classical and pseudobulge categories based on their position on the Kormendy diagram. Dividing our sample into bins of galaxy stellar mass, we find that the fraction of S0 galaxies hosting a classical bulge is significantly higher than the classical bulge fraction seen in spirals even at fixed stellar mass. We have compared the bulge and the global properties of spirals and S0 galaxies in our sample and find indications that spiral galaxies which host a classical bulge, preferentially get converted into S0 population as compared to pseudobulge hosting spirals. By studying the star formation properties of our galaxies in the $NUV - r$ color-mass diagram, we find that the pseudobulge hosting spirals are mostly star forming while the majority of classical bulge host spirals are in the green valley or in the passive sequence. We suggest that some internal process, such as AGN feedback or morphological quenching due to the massive bulge, quenches these classical bulge hosting spirals and transforms them into S0 galaxies, thus resulting in the observed predominance of the classical bulge in S0 galaxies.

Key words: galaxies: bulges – galaxies: formation – galaxies: evolution

1 INTRODUCTION

S0 galaxies are a class of galaxies with absent (or very faint) spiral arms in their disc. Traditionally, these galaxies are regarded as an intermediate transition class between two other major morphological classes, namely ellipticals and spirals, on the Hubble tuning fork diagram (Hubble 1936). The formation and evolution of S0 galaxies is a field of active research and a major effort has been carried out to understand their nature. S0 galaxies are considered as transformed spiral galaxies (Barway et al. 2009) and their formation scenarios can be broadly classified into two categories. The first category of morphological transformation is the one driven by mergers or other gravitational interactions with neighbouring galaxies. A spiral galaxy undergoing a major merger with a companion of similar mass or undergoing a series of minor mergers with smaller (with mass ratio 1:7 or more) companions can transform into an S0 galaxy (Querejeta et al. (2015); Tapia et al. (2017) and references therein). Tidal interaction and harassment of a spiral galaxy residing in a dense environment with its neighbouring galaxies can also lead to disappearance of spiral arms in the disc (Moore et al. 1996; Mihos 2003). The second category of formation scenario explains the formation of S0 galaxies via quenching of star formation in the progenitor spiral galaxy. This quenching can happen either due to environmental processes or by some internal mechanism. Environmental quenching of star formation can take place due to processes like ram pressure stripping, tidal interaction and halo quenching or starvation (Gunn & Gott 1972; Moore et al. 1996; Larson et al. 1980; Peng et al. 2015) which are characteristic of galaxy clusters and large groups having a massive dark matter halo, while internal quenching can be due to AGN feedback or stability of disc against star formation due to a massive bulge etc. (Cox et al. 2006; Martig et al. 2009). All of the above mentioned processes are the potential ways to transform a spiral galaxy into an S0 galaxy via disc fading and disappearance of spiral arms. (Dekki et al. 2002; Barway et al. 2007, 2009;
logical classes one must account for this environmental bias. Therefore, for galaxies in high density environments, a higher mass spiral, which is more likely to host a classical bulge, might get preferential conversion of classical bulge host spirals into S0 galaxies out of spirals changes the bulge type or is it due to processes such as major mergers or by sinking and coalescence of giant gas clumps found in high redshift discs (Elmegreen et al. 2008; Kormendy 2016). They are kinematically hot, featureless spheroids following the same scaling relations on the fundamental plane (Djorgovski & Davis 1987) as elliptical galaxies. Pseudobulges are thought to be formed by the slow rearrangement of gaseous material from the disc to the central region of galaxies, driven by non-axisymmetric structures such as bars, ovals etc., or via minor mergers (Eliche-Moral et al. 2011; Kormendy & Kennicutt 2004). Pseudobulges are rotationally supported systems having discy morphology and mixed stellar populations. Even though the two types of bulges differ in their properties from one another, one finds that both the types are hosted by spirals and S0 galaxies. However, the interesting fact is that while the frequency of occurrence of classical and pseudobulges is comparable in spiral galaxies, S0 galaxies prefer to host a classical bulge. The fraction of S0 galaxies which host a pseudobulge is a rather low value which ranges from 7.5% to 14% as quoted in literature, while for spirals this value ranges from 32% to 42.5% (Gadotti 2009; Vaghmare et al. 2013; Mishra et al. 2017b).

If S0 galaxies are transformed spirals, then naively one expects the classical bulge (or pseudobulge) fraction to be roughly equal in both spirals and S0 galaxies, unless the process which makes an S0 galaxy out of a spiral galaxy also changes the bulge type. Then it becomes interesting to ask the question: why do S0 galaxies prefer to host a classical bulge? Is it because the process which forms majority of S0s out of spirals changes the bulge type or is it due to preferential conversion of classical bulge host spirals into S0 galaxies?

One must, however, be watchful of, the observational biases that creep in while comparing the bulge fraction in the two morphological classes. Previous studies on galaxy bulges have shown that classical bulges are more commonly found in high mass galaxies and in galaxies residing in a denser environment (Fisher & Drory 2011; Kormendy 2016; Mishra et al. 2017a). This might introduce a bias in the comparison of classical bulge fraction in spiral and S0 galaxy population because S0 galaxies are more commonly found in high density environments and, are on an average more massive compared to spirals. It is also known that galaxy stellar mass and environment are correlated and one finds more massive galaxies in high density environments. A higher mass spiral, which is more likely to host a classical bulge, might get transformed into an S0 galaxy due to quenching of star formation due to environmental processes such as ram pressure stripping, starvation, tidal interaction etc. Therefore, for a comparison of classical bulge fraction in these two morphological classes one must account for this environmental bias.

or, at the very least, minimise this bias while choosing the galaxy sample.

In this work, we have explored the possible reason for the observed mismatch between classical bulge fraction in spirals and S0 galaxies. Forming a sample of spirals and S0 galaxies in a fixed environment, we compare the global and bulge properties of these two morphological classes in fixed bins of mass. The organization of this paper is as follows, Section 2 describes our data and sample selection. In Section 3 we present our results which are discussed in Section 4 before we present the summary of findings and interpretations in Section 5. Throughout this work, we have used the WMAP9 cosmological parameters: $H_0 = 69.3 \text{ km s}^{-1}\text{Mpc}^{-1}$, $\Omega_m = 0.287$ and $\Omega_{\Lambda} = 0.713$.

## 2 DATA AND SAMPLE SELECTION

In order to construct a statistically significant sample for our study, we start with data provided in the Nair & Abraham (2010) catalogue which is a catalogue of visual morphological classification for about 14,000 spectroscopically targeted galaxies in the SDSS DR4. The Nair & Abraham (2010) catalogue is a flux limited sample with an extinction corrected limit of $g < 16 \text{ mag}$ in the SDSS g band, spanning the redshift range $0.01 < z < 0.1$. In addition to visual morphology information for each galaxy given in the form of the Hubble T type, the catalogue also lists other relevant quantities for each object such as stellar mass taken from Kauffmann et al. (2003), fifth nearest neighbour environmental density from Baldry et al. (2006), group membership information and host dark matter halo mass taken from Yang et al. (2007). To obtain information of structural parameters of these galaxies, we cross matched the Nair & Abraham (2010) catalogue with data provided in Simard et al. (2011) catalogue. Simard et al. (2011) is a catalogue of two dimensional, point-spread-function-convolved, bulge+disc decompositions in the $g$ and $r$ bands for a sample of 1,123,718 galaxies from the SDSS DR 7. The cross match resulted in 12,063 galaxies.

Simard et al. (2011) fit each galaxy with three different models of the light profile: a pure Sérsic model, an $n_b = 4$ bulge + disc model, and a Sérsic (free $n_b$) bulge + disc model. They also provide an F-test probability criterion based on which one can choose the most appropriate model of light profile for a given galaxy. Since we are interested in studying bulges of disc galaxies, we have chosen only those galaxies where a bulge+disc model is preferred over a single Sérsic model. For the elliptical galaxies in our sample, we chose to use $n_b = 4$ bulge + disc model as we have found that majority of ellipticals in our sample are better fitted by this model as compared to the Sérsic (free $n_b$) bulge + disc model. We chose the $n_b$ bulge + disc model for the disc galaxies in our sample as it is known from the literature (Graham 2001; Balcells et al. 2003; Barway et al. 2009) that bulges of S0s and spirals span a wide range of values of the Sérsic index.

After making an appropriate choice of light profile model for each galaxy in our sample, we retain only those galaxies for which we have a reliable estimate of bulge Sérsic index ($n_b$). We do not discuss the reliability of $n_b$ estimate in this paper. This has been discussed in our previous
work (Mishra et al. 2017b) and we adopt the same criteria to exclude unreliable fits. Interested readers are referred to Mishra et al. (2017b) for details.

We have identified galaxies which host a bar using the flag provided in Nair & Abraham (2010), and have removed them from our sample as Simard et al. (2011) does not take bar into account in their fits and this might cause significant error in the estimation of bulge parameters. Application of these selection cuts on the initial sample of 12,063 galaxies leaves us with a sample of 1742 ellipticals and 4697 disc galaxies which we refer to as the parent sample in this paper.

For a comparative study of bulge fraction in spiral and S0 galaxies, one must account for the previously mentioned environmental bias in the sample. In order to do this, we chose to restrict our sample in a sufficiently narrow and low density regime of environmental parameter space. The distribution of stellar mass and environmental density parameter (Σ) measuring the fifth nearest neighbour density for the galaxies in our parent sample are shown in left and middle panels of Figure 1 respectively. We restricted our sample of spirals and S0 galaxies in the bin of log Σ where the distribution peaks. This bin has range $-0.75 < \log \Sigma < -0.35$ and corresponds to an intermediate to low local density environment. We further impose a cut based on the dark matter halo mass to which a certain galaxy belongs. We have taken only those galaxies where the mass of the host dark matter halo is less than $10^{12} M_\odot$. This is the halo mass limit above which mechanism of quenching of star formation due to starvation dominates (Dekel & Birnboim 2006). Application of these two cuts on environment leaves us with a sample of 170 S0 and 353 spiral galaxies. We refer to this sample as the reduced sample. This sample consists mainly of field galaxies or galaxies residing in small groups, the largest of which has 7 members. For the reduced sample, environment has little influence.

After accounting for the environmental bias, we plan to compare the bulge fraction in S0 and spiral galaxy population in fixed bins of stellar mass. We also want to see if the same class of bulges hosted by spiral and S0 galaxies are different in some of their properties which might help us to explain the observed mismatch in the bulge fraction. We have the available measurements of central velocity dispersion, probing the kinematics of central region of galaxies, from Nair & Abraham (2010) catalogue. We also obtained information on the central stellar population parameters like the $D_n(4000)$ index (as defined in Balogh et al. (1999)) from the table $galSpecIndx$ using the SDSS DR13. All of these measurements are derived from galaxy spectra coming from the central 3 arcsecond diameter of each object as probed by the SDSS fibre aperture. We wanted these values to be representative of bulge region of galaxies. But the galaxies in our sample have different sizes and are distributed across the redshift range $0.01 < z < 0.1$ and therefore there is a chance that bulge light coming from the central 3 arcsecond is contaminated significantly by the disc light. In order to minimise this contamination, we found the radius at which disc light starts to dominate the bulge light by plotting light profiles of disc and the bulge from Simard et al. (2011) decompositions. We demanded that for all the galaxies in the reduced sample this radius should be greater than or equal to the radius of the SDSS fibre aperture. Application of this criterion gave us our final sample of 155 S0 and 262 spiral galaxies. The mass distribution of the final sample is plotted in the right panel of Figure 1.

3 RESULTS

3.1 Bulge classification

We have classified bulges into classical and pseudobulge types based on their position on the Kormendy diagram (Kormendy 1977). This diagram is a plot of the average surface brightness of the bulge within its effective radius $<\mu_e>$ against the logarithm of the bulge effective radius $r_e$. This bulge classification scheme which makes use of the Kormendy diagram was proposed by Gadotti (2009). Elliptical galaxies are known to obey a tight linear relation on this diagram. Classical bulges being structurally similar to elliptical galaxies follow the same scaling relation. Pseudobulges, on the other hand are structurally different from ellipticals and hence they lie away from this relation. Gadotti (2009) has proposed that bulges which deviate more that three times the r.m.s. scatter from the best fit relation for ellipticals be classified as pseudobulges while those falling within this scatter be classified as classical bulges. This physically motivated bulge classification has also been used in recent works (Vaghmare et al. 2013; Neumann et al. 2017; Mishra et al. 2017b).

The Kormendy relation for our sample was obtained

![Figure 1](image-url)
by fitting ellipticals in our parent sample using $r$ band data. The equation for the best fit line is

$$\langle \mu_b (r_e) \rangle = (2.330 \pm 0.047) \log(r_e) + (18.160 \pm 0.024)$$

The rms scatter in $\langle \mu_b (r_e) \rangle$ around the best fit line is 0.429. All galaxies which lie away more than 3 sigma scatter from this relation are classified as pseudobulge hosts while those within this scatter are classified as classical bulge hosts.

After application of this criterion, we find that out of 262 spiral galaxies in our final sample the number of classical and pseudobulge hosts are 109 (41.6%) and 153 (58.4%) respectively. For the total 155 S0 galaxies, we find 129 (83.2%) of them host a classical bulge while the rest 26 (16.8%) are pseudobulge hosts. One can already notice the large mismatch between the fraction of classical bulge host galaxies in spiral and S0 morphology class even in fixed environment. We now divide the mass range of our final sample in 6 different stellar mass bins. The stellar mass bin divisions are log($M_{\star}/M_{\odot}$) = [8.2, 8.8, 9.4, 10.0, 10.6, 11.2, 11.8], and Table 1 contains the relevant number and fraction of classical and pseudobulge hosting spiral and S0 galaxies in each bin of stellar mass. One can notice from Table 1 that fraction of galaxies which host a classical bulge increases with increase in mass for both the galaxy morphologies. But the interesting thing to note is that in all the mass bins which have enough galaxies for a statistically meaningful comparison, the classical bulge fraction in S0 galaxies is significantly higher as compared to the spirals. This confirms the notion that the observed mismatch between classical bulge fraction in spiral and S0 galaxies is not driven by any environmental or mass biases of the sample, but is an observational fact.

3.2 Bulge and global properties of S0 and spiral galaxies

We first try to see if there is any difference in properties of the same bulge type hosted by spirals and S0 galaxies by comparing them with respect to their kinematics and stellar populations. We have used the velocity dispersion ($\sigma$) and the 4000 Å spectral break index ($D_4(4000)$) to study the kinematics and the stellar population of the bulge respectively. The break in the galaxy optical spectrum at 4000 Å arises due to accumulation of stellar absorption lines (of mainly metals) in the atmosphere of old stars and lack of hot young stars. This break, quantified by the $D_4(4000)$ index, is larger for the galaxies having older stellar populations. The $D_4(4000)$ index is a reliable indicator of the mean age of galaxy stellar populations and value of $D_4(4000)$ ~ 1.3 and $D_4(4000)$ ~ 1.8 represents a stellar population having light weighted mean stellar ages of ~ 1-2 Gyr and ~ 10 Gyr respectively (Kauffmann et al. 2003). To carry out the comparison, we have divided our final sample of spirals and S0 galaxies in four mass bins with divisions log($M_{\star}/M_{\odot}$) = [8.5,9.4,10.0,10.6,11.5] and have plotted them on $D_4(4000)$ – $\sigma$ plane for each stellar mass bin as shown in Figure 2. The plots have been divided into four quadrants by two lines given by $D_4(4000)=1.5$ and $\sigma=130$ km/s. The line at $D_4(4000)=1.5$ has been used to divide bulges having a young (with $D_4(4000)<1.5$ ) and an old ($D_4(4000)\geq1.5$) stellar population. A value of $D_4(4000)=1.5$ corresponds to a stellar age of ~ 2 Gyr. In recent literature (Zahid & Geller 2017), this value has been used to select old and passive galaxies. The line at $\sigma=130$ km/s has been put as a consistency check on our bulge classification and to identify spurious pseudobulges. Fisher & Drory (2016) have suggested that if a bulge is found to have a central velocity dispersion greater than 130 km/s , then it is most likely to be a classical bulge. Therefore, any pseudobulge, in our sample, if found to have $\sigma>130$ km/s has a high chance of being a misclassified pseudobulge.

3.3 Bulge bulge scatter from this relation are classified as pseudobulge hosts. One can already notice the large mismatch between the fraction of classical bulge host galaxies in spiral and S0 morphology class even in fixed environment.

| Mass range (log($M_{\star}/M_{\odot}$)) | 8.2 - 8.8 | 8.8 - 9.4 | 9.4 - 10.0 | 10.0 - 10.6 | 10.6 - 11.2 | 11.2 - 11.8 |
|---------------------------------------|-----------|-----------|-----------|-----------|-----------|-----------|
| No. of spiral galaxies                | 2         | 19        | 42        | 127       | 68        | 4         |
| Pseudobulge host spirals              | 2         | 18        | 36        | 71        | 25        | 1         |
| Classical bulge host spirals          | 0         | 1         | 6         | 56        | 43        | 3         |
| Spiral classical bulge fraction (%)  | 0         | 5.3       | 14.3      | 44.1      | 63.2      | 75        |
| No. of S0 galaxies                    | 2         | 6         | 23        | 97        | 25        | 2         |
| Pseudobulge host S0s                  | 2         | 5         | 10        | 8         | 1         | 0         |
| Classical bulge host S0s              | 0         | 1         | 13        | 89        | 24        | 2         |
| S0 classical bulge fraction (%)       | 0         | 16.7      | 56.5      | 91.7      | 96.0      | 100       |
thus indicates that the classical bulges hosted in spirals and S0 are not different but are similar in their kinematics and stellar population properties.

After comparing the properties of bulges, we now compare the global properties of galaxies in our final sample using the galaxy size-mass relation. In the left panel of Figure 3 we have plotted the effective radius ($R_e$) versus total stellar mass for all classical and pseudobulge host spiral and S0 galaxies in our final sample. The galaxy semimajor axis effective radius ($R_e$) has been taken from Simard et al. (2011) and the stellar mass estimates are taken from Kauffmann et al. (2003). The lines passing through each population on this size-mass plot are best fitted straight lines for each population. The plot tells us that pseudobulge hosting spiral galaxies have bigger sizes as compared to classical bulge hosting spirals at similar masses. One can also simultaneously see the similarity of mass size relation between spiral and S0 galaxies which host a classical bulge.

4 DISCUSSION

We now discuss the probable reason for the observed mismatch of bulge fraction seen in spirals and S0s in the light of results presented in the previous section. We know that morphological transformation of spirals into S0 galaxies can happen through a number of processes. These include the processes driven by interaction with other galaxies, e.g. major and minor mergers, tidal harassment etc., or morphological transformation via disc fading due to the shut down of star formation by environmental processes such as ram pressure stripping (Gunn & Gott 1972) of disc gas or quenching due to starvation (Larson et al. 1980), or by some internal processes like supernova and AGN feedback (Cox et al. 2006; Croton et al. 2006) or by making the disc stable against star formation due to a massive bulge (Martig et al. 2009). All these processes can change the properties of progenitor spirals in some way or another and hence, the interpretation of the difference seen in bulge fraction in the two morphological types gets linked to the formation scenario of S0 galaxies. As a next step, we discuss the possible ways in which the observed mismatch in classical bulge fraction seen in spirals and S0s can be explained and, how the individual process of morphological transformation fits into the overall picture.

If S0 galaxies are transformed spirals then one can think of two possible reasons which can explain the observed mismatch in classical bulge fraction seen in S0 and their supposed progenitors, the spiral galaxies. The first possibility is that the process which transforms spirals into S0 galaxies also changes the bulge type. One mechanism to do so is through galaxy mergers. A major merger of a pseudobulge host spiral with a similar galaxy can produce a classical bulge hosting S0 galaxy and thus increase the classical bulge fraction in the remnant population (Kormendy 2016; Tapia...
In their study, López-Sanjuan et al. (2009) have found that only 8% of present massive disc galaxies (having stellar mass $>10^{10} M_\odot$) might have undergone a disc-disc major merger since since $z=1$, implying that disc-disc major mergers are not very frequent for the past $\sim 7$ Gyr. This value of merger fraction does not seem to be high enough for significantly changing the classical bulge fraction in the population of merger remnants. Moreover, major mergers of spiral galaxy do not always produce classical bulges and S0 galaxies. In addition to producing elliptical galaxy like remnants via major mergers, recent simulations have also formed a spiral with late type morphology hosting a pseudobulge in major mergers of spiral galaxies (Sauvaget et al. 2018). Finally, a major or a series of minor merger of a pseudobulge hosting spiral galaxy with other galaxies will produce a remnant which is bigger in size than the pseudobulge hosting spirals. If majority of classical bulge hosting S0s are produced by this process, one would have them lying above the pseudobulge hosting spirals in size-mass plane which is not seen in the size-mass relation as shown in the left panel of Figure 3. Therefore, it seems unlikely that major merger is a dominant reason for the observed mismatch seen in classical bulge fraction of spirals and S0 galaxies.

The other possibility which can explain the observed mismatch of classical bulge fraction is that of preferential transformation of classical bulge hosting spirals to S0 morphology and thus increasing the observed classical bulge fraction as compared to the spiral progenitors. The results that we have presented till now, do not oppose the possibility of preferential conversion of classical bulge host spirals to S0 population without changing the bulge type. A spiral galaxy can gravitationally interact with neighbouring galaxies via fly-by interactions and the global tidal field of the environment which can lead to disappearance of spiral arms (Moore et al. 1999; Bekki & Couch 2011). There are simulations which show that the spirals having higher central surface brightness are more prone to loosing spiral arms due to tidal interactions as compared to the spirals with low central surface brightness (Moore et al. 1999). Usually the surface brightness of a typical classical bulge is higher than a typical pseudobulge (Gadotti 2009) and hence there exists a possibility that spirals hosting classical bulges are more likely to transform into an S0 galaxy. However, these simulations have been performed in cluster environment where galaxy-galaxy gravitational interactions are numerous and tidal fields are strong. The galaxies in our sample are selected from a less dense environment. We have checked the available group membership information for the galaxies in our sample from Yang et al. (2007). Out of total 417 galaxies in our final sample we have group membership information for 393 objects. We find that out of these 393 galaxies, 296 of them are isolated galaxies and almost all other galaxies reside in groups having 4 or less members. Therefore, it is unlikely that the galaxies in our sample are experiencing strong tidal interaction which is the characteristic of dense cluster environment. For this reason, we believe that the mechanism of tidal interaction due to environment is not driving the discrepancy in classical bulge fraction by selectively converting classical bulge hosting spirals to S0 morphology.

We now consider the next process which can convert spirals to S0 galaxies without altering the bulge type. A process...
which simply shuts down the star formation in the disc of spiral galaxy can lead to fading of spiral arms and result in formation of a S0 galaxy without significantly altering bulge kinematics and global properties of the galaxy such as size and mass. Removal of gas from the disc or stopping the fresh infall of gas from the surrounding can lead to disappearance of spirals arms (Bekki et al. 2002) and make the galaxy disc passive (Bekki 2009). Therefore, if pseudobulge hosting spirals remain star forming while majority of classical bulge host spirals are undergoing star formation shut down then the resulting population of S0 galaxies will be dominated by classical bulge hosts. The population of S0 galaxies created in this manner will also have similar bulge properties and will lie in the same size-mass parameter space as classical bulge host spirals as is seen in the results presented in the previous section.

We tried to investigate this possibility by studying the star formation property of classical and pseudobulge hosting spirals and S0 galaxies on NUV-r color-mass diagram which is shown in the right panel of Figure 3. The NUV magnitudes for the galaxies in our sample were obtained from the Reference Catalog of Spectral Energy Distributions (RCSED) (Chilingarian et al. 2017) which is a value-added catalogue of 800,299 spectroscopically targeted SDSS galaxies in 11 ultraviolet, optical, and near-infrared bands. We obtained the r band model magnitude from the SDSS DR 13 database. In the NUV − r color mass diagram, the two horizontal lines at NUV = 5 and NUV = 4 mark the boundary of the green valley region (Salim 2014). The galaxies lying above the green valley in the NUV − r color-mass diagram are in the non star forming (quenched) sequence while galaxies lying below the green valley are star forming. One can notice from this plot that most of spiral galaxies seen in quenched sequence are dominated by classical bulge hosting spirals. On the other hand, most of the pseudobulge hosting spirals are star forming.

The above result supports our hypothesis that the observed mismatch between classical bulge fraction in spirals and S0s is due to the fact that spirals which host a classical bulge are preferentially getting converted into S0 morphology via quenching of star formation. The reason for this correlation between bulge type and star forming rate and what causes this quenching is not clear. However, we do have some clues which can shed some light on these questions. Processes such as ram pressure stripping of disc gas in cluster environment and virial shock heating of infalling gas due to massive dark matter halo can quench a galaxy (Gunn & Gott 1972; Bekki 2009; Dekel & Birnboim 2006). Since our final sample spans a narrow range of environment, and is dominated by galaxies in the field and in small groups having a low mass dark matter halo (< 10^{12}M_{\odot}), we can safely say that quenching due to environment, which operates strongly in clusters, cannot be a dominant process. The other possibilities include quenching due to major mergers or due to some internal processes such as AGN feedback. Recently Weigel et al. (2017) have shown that major mergers are not a dominant process for galaxy quenching and at any given stellar mass the merger quenched galaxies account only for 1-5 % of the quenched population since last 5 Gyr. Therefore, the most probable quenching mechanism for the galaxies in our sample seems to quenching due to some internal process.

Quenching via internal means can happen due to a number of mechanisms. One way to make disc passive is by expulsion of disc gas through winds driven by intense star formation or supernova feedback. But simulations have also shown than quenching due to supernova feedback is not enough to sufficiently affect the star formation in the disc (Gabor et al. 2010 and references therein). One often evokes the feedback from AGN as an additional means to inject energy in the surrounding, leading to heating of gas and preventing fresh gas infall which leads to quenching. Bluck et al. (2016) have studied the correlation between a variety of galactic and environmental properties and quenching of star formation. They have found that at fixed environment, there is a tight correlation between central velocity dispersion and fraction of quenched galaxies. They speculate that the reason for this correlation is because the central velocity dispersion and black hole mass of a galaxy are correlated. A galaxy having higher velocity dispersion will host a more massive black hole which then can shut down the star formation in the disc via more energetic AGN feedback. We have seen in Figure 2 that classical bulges have higher velocity dispersion as compared to the pseudobulges. Therefore, as discussed before, there is a possibility that the classical bulge host spirals are getting quenched due to black hole feedback.

There are other possible internal quenching mechanisms like morphological quenching (Martig et al. 2009) where bulge dominated galaxies stabilize their discs against star formation due to the presence of a massive bulge. The stability of the disc against star formation leads to quenching of the galaxy with time. This quenching mechanism also predicts that the bulge dominated galaxies form stars less efficiently as compared to the the disc dominated ones. It is known that the bulge to total light ratio is usually found to be higher in classical bulge hosting disc galaxies as compared to the ones hosting pseudobulges (Kormendy 2016). This makes the classical bulge hosting disc galaxies bulge dominant and hence, it is possible that these galaxies are more likely to get quenched morphologically.

All of the mechanism discussed above can lead to disc fading in classical bulge hosting spiral galaxies and can potentially transform them into S0 galaxies. However, we do not have sufficient information to conclusive infer which internal quenching mechanism is actually dominant. The details of internal quenching and how it explains the observed correlation between bulge type and the star formation properties of galaxies is beyond the scope of this work. In future, we would like to study the star formation history of a sample of isolated spirals and S0 galaxies in low density environment by making use of spectroscopic information. Such a study will be valuable for shedding some light on the formation of S0 galaxies in low density environments.

5 SUMMARY

In this work we have tried to understand the possible reason for the significant difference seen in the classical bulge fraction in the spiral and S0 galaxy population in the nearby Universe. We have constructed a sample of 262 spiral and 155 S0 galaxies in a fixed narrow range of environment and then have classified their bulges in classical or pseudobulges types using the Kormendy diagram. Dividing the sample into bins of stellar mass, we have compared the classical
bulge fraction in spirals and S0 galaxies. We have found that, even at fixed stellar mass, the fraction of galaxies hosting a classical bulge is higher in S0 galaxies compared to spirals. If S0 galaxies are transformed spirals, then this can happen either due to change of bulge type during this morphological transformation or it can be due to a process by which classical bulge hosting spirals are more likely to get converted into S0 morphology as compared to pseudobulge hosting spirals. Comparing the bulge and global properties of spirals and S0, we rule out the possibility that the change of bulge type during morphological transformation being a dominant process and find that classical bulge hosting spirals are the likely progenitors of classical bulge hosting S0 galaxies. By studying the star formation properties of these galaxies we find that majority of pseudobulge hosting spirals are star forming while those hosting classical bulges are either in green valley or are in the passive sequence. We think that some internal quenching mechanism such as feedback due to central supermassive black hole or stability of gas disc against star formation due presence of a massive bulge (morphological quenching), shuts down the star formation in these classical bulge host spirals and transforms them into classical bulge hosting S0 galaxies. It is this process that gives rise to the high classical bulge fraction in S0 galaxies.

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