Pseudo bulges in galaxy groups: the role of environment in secular evolution

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ABSTRACT
We examine the dependence of the fraction of galaxies containing pseudo bulges on environment for a flux limited sample of ∼5000 SDSS galaxies. We have separated bulges into classical and pseudo bulge categories based on their position on the Kormendy diagram. Pseudo bulges are thought to be formed by internal processes and are a result of secular evolution in galaxies. We attempt to understand the dependence of secular evolution on environment and morphology. Dividing our sample of disc+bulge galaxies based on group membership into three categories: central and satellite galaxies in groups and isolated field galaxies, we find that pseudo bulge fraction is almost equal for satellite and field galaxies. Fraction of pseudo bulge hosts in central galaxies is almost half of the fraction of pseudo bulges in satellite and field galaxies. This trend is also valid when only galaxies are considered only spirals or S0. Using the projected fifth nearest neighbour density as measure of local environment, we look for the dependence of pseudo bulge fraction on environmental density. Satellite and field galaxies show very weak or no dependence of pseudo bulge fraction on environment. However, fraction of pseudo bulges hosted by central galaxies decreases with increase in local environmental density. We do not find any dependence of pseudo bulge luminosity on environment. Our results suggest that the processes that differentiate the bulge types are a function of environment while processes responsible for the formation of pseudo bulges seem to be independent of environment.

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

1 INTRODUCTION
Recent progress in our understanding of the central component of disc galaxies has expanded our knowledge of galaxy formation and evolution. We now know that the central component i.e. the bulge, comes in two flavours. Classical bulges are thought to be formed by mergers (Aguerri et al. 2001) or sinking of giant gas clumps found in high redshift discs to central region of the galaxy and formation of these bulges through violent relaxation and starbursts (Dekel et al. 2009; Cacciato et al. 2012; Forbes et al. 2014; Kormendy 2016). Pseudo bulges on the other hand are thought to be the product of internal processes and have secularly evolved through time (Kormendy & Kennicutt 2004). Difference in the formation scenario for these two bulge types makes them fundamentally different from one another, which is also reflected in their distinct properties. Pseudo bulges exhibit nuclear morphological features which are characteristic of galaxy discs such as a nuclear bar, spiral or ring (Carollo et al. 1998) while classical bulges are featureless. Also, pseudo bulges are composed of a younger stellar population with a flatter radial velocity dispersion profile as compared to that of classical bulges (Gadotti 2009; Fabricius et al. 2012). The two types of bulges behave differently with respect to several well known correlations between structural parameters of galaxies. For example, Gadotti (2009) has shown that the two bulge types occupy different regions of the parameter space, when plotted as different projections of the fundamental plane (Djorgovski & Davis 1987). A smooth transition from one type of bulge to another as seen in these correlations also points to possible existence of composite bulges with mixed properties (Gadotti 2009; Fisher & Drory 2010). Properties of composite bulges have been explored in detail in recent works for e.g. Erwin et al. (2015) but much work is
needed to put strong limits on the frequency of occurrence of composite bulges in galaxies.

Most previous work on bulges (Carollo et al. 1998; Fisher & Drory 2008; Gadotti 2009; Fabricius et al. 2012) has focussed on the relation between bulges and properties of their host galaxies, which in turn, have been used as criteria for classification of bulge type. As a result, there has been a significant increase in our understanding of the importance of bulges in the evolution of their host galaxies and associated black holes, AGN etc. (Gadotti & Kauffmann 2009; Kormendy et al. 2011; Fernández Lorenzo et al. 2014; Vaghmare et al. 2015). At this time there exist a number of simulations which are successful in forming classical bulges via mergers (Aguerri et al. 2001) or via clump instabilities (Elmegreen et al. 2008). Also, our understanding of secular evolution is now detailed enough to qualitatively explain commonly occurring morphological features in galaxies such as nuclear rings, nuclear bars and pseudo bulges. It has been shown in simulations that bar driven secular evolution can form inner and outer rings, pseudo bulges and structure that resemble nuclear spirals as observed in disc galaxies (Simkin et al. 1980; Sanders & Tubbs 1980; Athanassoula 1992; Salo et al. 1999; Rautiainen & Salo 2000). On the other hand, studies attempting to quantitatively understand the process of secular evolution in diverse environments are not very common in the literature.

A study of the Virgo cluster by Kormendy et al. (2009) shows that 2/3 of stellar mass is in elliptical galaxies alone. Information on other extreme of environmental density regime comes from Fisher & Drory (2011). By studying galaxies within the local 11 Mpc volume in low density regions, they report that 1/4 of stellar mass is contained within ellipticals and classical bulges while rest 3/4 of mass is distributed in pseudo bulges, discs and bulge-less galaxies. These two observations have led the authors to conclude that the process driving distribution of bulge type appears to be a strong function of environment. There are only a few works which explore the effect of environment specifically on bulges. Hudson et al. (2010) have studied the colour of bulges and discs in clusters and found that the bulge colour does not depend on environment. Lackner & Gunn (2013) distinguished between galaxies having a quiescent bulge and a star forming bulge based on the strength of the 4000 Å break ($D_n(4000)$ index). They have associated quiescent bulges with classical bulges and star forming bulges with pseudo bulges. In their work, the classical bulge profile is modelled as having de Vaucouleurs profile with bulge Sérsic index $n_b = 4$ and pseudo bulges are modelled with an exponential profile with $n_b = 1$. Using fifth projected neighbourhood density as a measure of local environment, they show a strong increase in fraction of galaxies hosting a classical bulge with increase in local density. On the other hand, fraction of galaxies hosting a pseudo bulge decreases slowly as one goes from a lower to a higher local density environment. Lackner & Gunn (2013) have focussed on studying the dependence of galaxy properties of classical bulges on the environment. There is a need to explore properties of pseudo bulges over a wide range of environmental density in order to expand our knowledge of secular evolution and make it more quantitative. Dependence of distribution of pseudo bulges and their intrinsic properties on environment will help us understand how environment affects the processes that govern distribution and formation of pseudo bulges.

In this work, we have explored the dependence of bulge type on environment as well as on galaxy morphology. Our sample spans a wide range of environmental density and is composed of mainly isolated/field morphology and galaxy groups with available morphological information for each object. We have identified and classified our sample of S0 and spiral galaxies into classical and pseudo bulge host galaxies. We further divide our sample by galaxy group association, into three categories: 1. field galaxies not belonging to any group, 2. galaxies which reside in the center of galaxy groups and 3. their satellite galaxies. We investigate the dependence of bulge type on environments in these three categories. The paper is organised as follows. Section 2 describes the data and sample selection. Section 3 describes our results and Section 4 summarizes the findings and the implications. Throughout this work, we have used the WMAP9 cosmological parameters: $H_0 = 69.3$ km s$^{-1}$Mpc$^{-1}$, \( \Omega_m = 0.287 \) and \( \Omega_L = 0.713 \). Unless otherwise noted, photometric measurements used are in the SDSS $r$ band. All logarithms are to base 10.

## 2 DATA AND SAMPLE SELECTION

To aim for a sample suitable for studying bulges in galaxy groups, we started with data from Meert et al. (2015) which provides a catalogue of nearly 700,000 spectroscopically selected galaxies drawn from the SDSS DR7 in SDSS $g$, $r$ and $i$ bands (Meert et al. 2016). This catalogue is a flux limited sample with $r$-band Petrosian magnitude for all galaxies having magnitude in range $14 < r < 17.7$ and provides 2D, PSF corrected de Vaucouleurs, Sérsic, de Vaucouleurs+Exponential and Sérsic+Exponential fits of galaxies with flags indicating goodness of the fit, using the PyMorph pipeline (Vikram et al. 2010).

We cross matched the Meert et al. (2015) catalogue with the data provided in Nair & Abraham (2010) which is a catalogue of detailed visual classification for nearly 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 $g < 16$ mag in SDSS $g$ band, spanning the redshift range $0.01 < z < 0.1$. In addition to morphological $T$-type classification it also provides measurements of stellar mass of each object taken from Kauffmann et al. (2003) which used stellar absorption-line indices and broadband photometry from SDSS to estimate the stellar mass of galaxies. The Nair & Abraham (2010) catalogue also contains information on average environmental density from Baldry et al. (2006) and information on galaxy groups from Yang et al. (2007) such as group mass, group luminosity, group halo mass, group richness etc. We have made use of all relevant information on individual galaxies and groups as provided in Nair & Abraham (2010) in our work. Our cross match of these two catalogues resulted in a sample of 8929 galaxies on which we have further imposed condition of a “good fit” as given in Meert et al. (2015) and which is described below.

To obtain our final sample of galaxies we have first removed galaxies with bad fits and problematic two component fits as indicated by flags in Meert et al. (2015). The
three categories of good fits in this catalogue are as follows.

(i) Good two component fits: which includes galaxies where both bulge and disc components have reliable estimates

(ii) Good bulge fits: which includes galaxies where disc estimates are unreliable while the bulge measurements are trustworthy

(iii) Good disc fits: which includes galaxies where bulge estimates are unreliable but the disc measurements are trustworthy.

Since the focus of this study is on bulges we have retained galaxies in the first two categories and have discarded those in the third one. Additional constraints comes from fact that two component fits with bulge Sérsic index $n \geq 8$ can be used for total magnitude and radius measurement but they have unreliable subcomponents. We have taken a conservative approach and have retained only the galaxies having bulge Sérsic index $n < 8$.

After applying all selection criteria mentioned above, we are left with 4991 galaxies, 2026 of which are spirals ($1 \leq T \leq 9$), 1732 are S0s ($-3 \leq T < 0$) and 1233 are ellipticals ($-4 \leq T \leq 0$). From here onwards, we will collectively refer to the population of spirals+S0s as disc galaxies. Out of the 3758 disc galaxies in our sample, we have information about the group properties of 3641 galaxies from Yang et al. (2007).

### Table 1: Number of classical and pseudo bulges in spiral and S0 galaxies in our sample

| Bulge type       | Disc galaxies | S0 | Spiral |
|------------------|---------------|----|--------|
| All bulges       | 3758          | 1732 | 2026  |
| Classical bulge  | 3227          | 1639 | 1688  |
| Pseudo bulge     | 431           | 93  | 338    |
| Pseudo bulge fraction (%) | 11.47 | 5.37 | 16.68 |

### Table 2: Distribution of elliptical galaxies in our sample into central, satellite and group categories.

|                | Central | Satellite | Field |
|----------------|---------|-----------|-------|
| All ellipticals| 1233    | 684       | 222   | 290   |

### Table 3: Number of classical and pseudo bulges in all disc galaxies classified as central, satellite and field galaxies.

| Bulge type       | Central | Satellite | Field |
|------------------|---------|-----------|-------|
| All bulges       | 1119    | 752       | 1770  |
| Classical bulge  | 1058    | 657       | 1516  |
| Pseudo bulge     | 61      | 95        | 254   |
| Pseudo bulge fraction (%) | 5.45 | 12.63 | 14.35 |
| Median galaxy stellar mass (log$M_\odot$) | 10.865 | 10.624 | 10.627 |

### Table 4: Number of classical and pseudo bulges in all S0 galaxies classified as central, satellite and field galaxies.

| Bulge type       | Central | Satellite | Field |
|------------------|---------|-----------|-------|
| All bulges       | 555     | 374       | 741   |
| Classical bulge  | 541     | 353       | 690   |
| Pseudo bulge     | 16      | 51        | 51    |
| Pseudo bulge fraction (%) | 2.52 | 5.61 | 6.88 |
| Median galaxy stellar mass (log$M_\odot$) | 10.854 | 10.617 | 10.605 |

### Table 5: Number of classical and pseudo bulges in all spiral galaxies classified as central, satellite and field galaxies.

| Bulge type       | Central | Satellite | Field |
|------------------|---------|-----------|-------|
| All bulges       | 564     | 378       | 1029  |
| Classical bulge  | 517     | 304       | 626   |
| Pseudo bulge     | 47      | 74        | 203   |
| Pseudo bulge fraction (%) | 8.33 | 19.58 | 19.73 |
| Median galaxy stellar mass (log$M_\odot$) | 10.877 | 10.629 | 10.651 |

### 3 RESULTS

#### 3.1 Identifying pseudo bulges

A common practice in studies of bulges is to classify them on basis of the Sérsic index. In this method, pseudo bulges are defined as those having Sérsic index below a certain threshold. Usually this threshold value is taken to be $n = 2$ (Ho & Kim 2014; Ribeiro et al. 2016). However, measurement of Sérsic index from ground based telescopes are reported to have errors as large as 0.5 (Gadotti 2008; Durbala et al. 2008). Also, Sérsic index $n$ and effective radius ($r_e$) have degenerate errors which leads to additional error in $n$ due to uncertainty in measurement in $r_e$. Hence, using a specific Sérsic index threshold for bulge classification may lead to ambiguity. Therefore, we have refrained from using the Sérsic index to classify bulges in favour of a better physically motivated classification criteria due to Gadotti (2009) which has been used in recent works for eg. Vaghmare et al. (2013).

This criteria involves classification of bulge types based on their position on the Kormendy diagram (Kormendy 1977). The Kormendy diagram is a plot of the average surface brightness of the bulge within its effective radius ($\mu_b(<r_e)$) against logarithm of effective radius $r_e$. Elliptical galaxies are known to obey a tight linear relation on this diagram. Classical bulges are thought to be structurally similar to ellipticals and therefore obey a similar relation while pseudo bulges being structurally different, lie away from it. Any bulge that deviates more that three times the r.m.s. scatter from the best fit relation for ellipticals is classified as pseudo bulge by this criterion (Gadotti 2009).

The Kormendy diagram for our sample is shown in Figure 1a. The best fit line was obtained by plotting elliptical galaxies using $r$ band data. The equation of the best fit line is

$$\langle \mu_b(<r_e) \rangle = (2.768 \pm 0.0306)\log r_e + 18.172 \pm 0.0255$$

The rms scatter in $\langle \mu_b(<r_e) \rangle$ around the best fit line is 0.414. The dashed lines encloses region of 3 times rms scatter from the fit. All galaxies lying outside the region enclosed by the dashed lines are taken to be pseudo bulges.

We have separated the disk galaxies having S0 and spi-
Figure 1. (a) Kormendy relation for elliptical galaxies. The solid line is best fit line to these ellipticals while the two dashed lines enclose 3σ scatter from best fit; (b) bulges of spiral galaxies; (c) bulges of S0 galaxies in our sample.

Figure 2. Distribution of (a) central velocity dispersion and (b) D_n(4000) index for classical and pseudo bulges in our sample. Both distributions have been normalised by area. Solid and dashed lines denote classical and pseudo bulge host galaxies respectively.

Figure 3. Stellar mass distribution of disk galaxies in our sample.


ceral morphology and have plotted them on the Kormendy diagram as shown in Figures 1b and 1c respectively. It is clear from these figures that the number of pseudo bulge host galaxies are higher in spirals than in S0 galaxies. We have found that out of 2026 spiral galaxies, 338 (16.68 percent of spiral population) host a pseudo bulge. On the other hand only 93 (5.37 percent of S0s) out of a total of 1732 number of S0 galaxies are pseudo bulge hosts. This result is summarised in Table 1.

To test the robustness of our classification criterion, we have compared the classical and pseudo bulges in our sample with respect to the properties in which two bulge types are expected to show different behaviour. Secularly evolved pseudo bulges, due to their disk like stellar kinematics are dynamically colder systems compared to the merger generated classical bulges. This property is reflected in the different values of velocity dispersion of the two bulge types. For eg. Fisher & Drory (2016) have shown that on an average pseudo bulges have lower central velocity dispersion than classical bulges. Classifying the bulge type based on the Sérsic index they have seen that pseudo bulges have average velocity dispersion $\sim 90$ km/s whereas this value is $\sim 160$ km/s for classical bulges. We have obtained the values of central velocity dispersion for the galaxies in our sample from Nair & Abraham (2010). After applying aperture correction, we have plotted the distribution of central velocity dispersion for classical and pseudo bulge host galaxies in our sample which is shown in Figure 2a. One can see a bimodal distribution of central velocity dispersion with respect to the bulge type. Pseudo bulges are found to have a lower value of central velocity dispersion, with their distribution peaking around $\sim 60$ km/s in contrast to the distribution of the same for classical bulges which peaks around $\sim 160$ km/s, in agreement with expected trends.
Previous studies (Gadotti & dos Anjos 2001; Fisher 2006) have also indicated that pseudo bulges exhibit star forming activity as opposed to classical bulges which are mainly composed of old stars. To separate old and young stellar population in galaxies, we have used the strength of the 4000 Å spectral break which arises due to accumulation of absorption lines of mainly metals in the atmosphere of old, low mass stars and by a lack of hot, blue stars in galaxies. The strength of this break is quantified by $D_n(4000)$ index. In literature, one can find several definition of this index which are available. In this work, we have used the definition of this index as provided in Balogh et al. (1999). A low value of $D_n(4000)$ index denotes young stellar population. We have taken the $D_n(4000)$ index measurement from SDSS DR7 MPA/JHU catalogue\(^1\) and have plotted it’s distribution for classical and pseudo bulges in our sample as shown in Figure 2b. As expected, our pseudo bulges have lower value of the $D_n(4000)$ index which peaks around value $\sim 1.2$ as compared to the classical bulges peaking around $\sim 1.8$. A similar bimodal distribution of $D_n(4000)$ index with respect to bulge types, has also been found in works (Fisher & Drory 2016) that employ only bulge Sérsic index cutoff $n = 2$ to classify bulges. Gadotti (2009) has compared this bimodal distribution of $D_n(4000)$ when bulges are classified using the Kormendy relation only and when classification is based on threshold bulge Sérsic index. They find that peaks of distribution of $D_n(4000)$ for classical and pseudo bulge are closer when bulges are identified using the Sérsic index as compared to distance between peaks when the Kormendy relation is used for classification. Our result for distribution of $D_n(4000)$ is consistent with trend reported in Gadotti (2009) which uses the Kormendy diagram for bulge classification. This gives support to the bulge classification criteria that we have used.

At this point, we would like to mention that our sample is a flux limited sample with an extinction corrected flux limit of $g < 16$ mag in the SDSS $g$ band which makes it biased towards bright and massive galaxies. In Figure 3 we have plotted the stellar mass distribution of disk galaxies in our sample. Its clear that our sample is biased towards massive galaxies. As will be seen in later part of this paper that pseudo bulges are more common in galaxies having low stellar mass. Hence, the result presented here on fraction of pseudo bulges is applicable only to bright and massive galaxies.

3.2 Bulge fraction as a function of environment

Nair & Abraham (2010) provides the information of group membership and number of galaxies in a particular group or group richness taken from Yang et al. (2007). Depending on group ID and group richness ($N_{gr}$) a flag has been provided which tells if a galaxy is the most massive member of the group or a satellite galaxy. To study the effect of environment on frequency of occurrence of bulge type, we have divided our sample in three categories. We use flags specified in Nair & Abraham (2010) catalogue to classify the galaxies as:

(i) Central galaxies: are the galaxies which are most massive in a particular group and have group richness $N_{gr} > 1$.

(ii) Satellite galaxies: are galaxies other than the central galaxy in groups with richness $N_{gr} > 1$.

(iii) Field galaxies: are galaxies having group richness $N_{gr} = 1$.

One should keep in mind the fact that a group as defined by Yang et al. (2007) refers to a collection of galaxies which reside in a common dark matter halo. Hence, according to this definition, clusters of galaxies having hundreds of members or just two neighbouring galaxies as long as they reside in same dark matter halo are labelled as groups. Table 2 provides number distribution of ellipticals in our sample which are central, satellite or field galaxies. Tables 3, 4 and 5 summarise the statistics of total number of galaxies specified as central, satellite and field galaxies in disc galaxies as well as in spiral and S0 galaxies separately. Comparing Tables 4 and 5 we see that the pseudo bulge fraction (defined as number of pseudo bulge hosts divided by total number of galaxies) in spirals is more than 3 times the fraction of pseudo bulge hosts in S0 galaxies. This applies to all three categories i.e. central, satellite and field galaxies of spiral and S0 morphology class. It is also interesting to note that for a specific morphology, the pseudo bulge fraction is similar for satellites and fields but becomes less than half of this value in central galaxies.

Fisher & Drory (2011) have reported a strong dependence of bulge type on host galaxy mass in low density environments. Since our sample spans a wide density range upto cluster environments, we checked the same dependence by plotting the fraction of bulge type across different mass bins of host galaxies. Mass of all galaxies in our sample is taken from Kauffmann et al. (2003) and the resulting plot is shown

\(^1\) [http://wwwmpa.mpa-garching.mpg.de/SDSS/DR7/](http://wwwmpa.mpa-garching.mpg.de/SDSS/DR7/)
Figure 5. Dependence of fraction of bulge type as function of average environmental density for (a) central galaxies, (b) satellite galaxies and (c) field galaxies. The colour scheme is same as in Figure 4.

Figure 6. Stellar mass - average environmental density 2D histogram for (a) all central disc galaxies in our sample; (b) pseudo bulge host central disc galaxies.

Figure 7. (a) Dependence of bulge fraction on bulge absolute magnitude. The colour scheme is same as in Figure 4; (b) bulge absolute magnitude - average environmental density 2D histogram for all disc galaxies in our sample and (c) for pseudo bulge host disc galaxies.

in Figure 4 which shows that the pseudo bulge fraction decreases with increase in host galaxy mass while the trend is reversed for classical bulge hosts. The errors are taken as Poisson on the total number of pseudo and classical bulges and have been propagated to determine error bars on pseudo and classical bulge fractions. It is also evident from Figure 4 that pseudo bulge hosts dominate when host galaxy mass is less than $10^{9.5} M_\odot$ while classical bulges are more common above this limit. Revisiting Tables 3, 4 and 5 with this information of stellar mass dependence of pseudo bulge hosts, we note that the median stellar mass of central, satellite and field galaxies is similar. So the fact that pseudo bulge fraction in central galaxies is half of the pseudo bulge fraction...
found in satellite and field galaxies seems to be an environmental effect.

We now explore the dependence of bulge fraction in central, satellite and field galaxies separately on average environmental density parameter $\Sigma$ which is available in Nair catalogue taken from Baldry et al. (2006). It is defined as $\Sigma = N/(\pi d^2_N)$ where $d_N$ is projected comoving distance to the $N$th nearest neighbour. Nair & Abraham (2010) catalogue gives a best estimate density obtained by calculating the average density for $N = 4$ and $N = 5$ with spectroscopically confirmed members only with entire sample. For each category (central, satellite, field) of galaxies, we have divided $\Sigma$ in different bins and in each of these bins we have calculated the fraction of galaxies hosting classical and pseudo bulges. Figures 5a, 5b and 5c shows the dependence of the fraction bulge type on average environmental density $\Sigma$ for central, satellite and disc galaxies respectively. A quick examination of these three plots tells us that within error bars pseudo bulge fraction in satellites and fields show very minor variation with respect to each other but we find a significant trend in pseudo bulge fraction with average environmental density. At lowest environmental densities pseudo bulge fraction in central galaxies is around 21% which steadily decreases and reaches about 5% and becomes constant within error bars for $\log \Sigma \geq 0.0$. A point to note here is that the total number of pseudo bulges in S0 galaxies (see Table 4) is significantly less than total number of pseudo bulges in spiral galaxies (see Table 5) in all three classes viz. central, satellite and disc galaxies. As a result, the number of pseudo bulge hosting S0 galaxies will also be significantly less as compared to number of pseudo bulge hosting spirals in each bin of environmental density. Hence these trends of pseudo bulge fraction with environmental density are driven by the larger number of spiral galaxies.

We need to check whether the dependence of pseudo bulge host central galaxies on environment is a direct effect or is an indirect effect induced by their common dependence on stellar mass. To do this, we have plotted a 2D histogram of galaxy stellar mass vs. average environmental density for all central disc galaxies to check for existence of any correlation. The resultant plot is shown in Figure 6a and we see no obvious dependence of stellar mass on average environmental density $\Sigma$. We checked the possibility that the high fraction of pseudo bulges as seen in the environmental density range $-1.5 < \log \Sigma < 0.5$ in central galaxies is due to the fact that galaxies having low stellar mass might be dominating in that density range. We have seen in Figure 4 that pseudo bulge hosts dominate below stellar mass $< 10^{9.5} M_{\odot}$. To find out the stellar mass distribution of pseudo bulge host central galaxies across environment, we have plotted 2D histogram of stellar mass vs. average environmental density ($\Sigma$) for only those central galaxies which host a pseudo bulge. This plot is shown in Figure 6b and it is clear that in the range $-1.5 < \Sigma < 0.5$ it is dominated with pseudo bulge hosts with mass $> 10^{9.5} M_{\odot}$ ruling out the possibility that for the central galaxies, high fraction of pseudo bulges seen in this density range is only a result of stellar mass dependence of pseudo bulge fraction. This result further provides support to the idea that the pseudo bulge fraction is dependent on environment.

To understand the influence of environment on intrinsic properties of bulge rather than their host galaxies, we have estimated the $r$ band absolute magnitude of the bulges in our sample. The dependence of bulge type on bulge absolute magnitude is shown in Figure 7a which shows that pseudo bulge fraction increases in low luminosity regime and the trend is reversed for classical bulge host figures. Figures 7b and 7c are 2D histogram plots of bulge absolute magnitude vs. average environmental density for classical and pseudo bulges in our sample respectively. Large scatter in these two plots readily tells us that there is no strong dependence of bulge luminosity on environment.

4 SUMMARY & DISCUSSION

We have presented a systematic study of bulges of disc galaxies in galaxy group environment. The groups are defined as galaxies that share the same dark matter halo as identified by Yang et al. (2007). We use position of bulge on Kormendy diagram as the defining criterion for determination of bulge type. We find that 11.47% of disc galaxies in our sample host pseudo bulges. Dividing this sample by morphology we find that 16.68% of spiral galaxies in our sample are pseudo bulge host while this percentage is 5.37% for S0 galaxies. Further division of galaxies into three group based categories of central, satellite and field galaxies tells us that for the satellite and field galaxies pseudo bulge fraction is similar. On the other hand, we find that pseudo bulge fraction in central galaxies is less than half of the fraction in satellite and field galaxies, irrespective of morphology.

We find a significant dependence of pseudo bulge fraction hosted by central galaxies on average environmental density where pseudo bulges are more likely to be found in low density environments. We hardly see any such dependence of pseudo bulge fraction on environment for satellite galaxies and those which are in the field. Since galaxies having mass $< 10^{9.5} M_{\odot}$ are dominated by pseudo bulge hosts, we also have checked if the trend of pseudo bulges in central galaxies with environment is an indirect effect of stellar mass dependence of bulge type. We find that inferred dependence of pseudo bulge hosting central galaxies on environment is a likely to be direct effect of environment.

If pseudo bulges are formed through internal processes and evolve secularly then it seems environment plays some role in affecting the process which determines distribution of bulge type. Our finding of higher number of pseudo bulges in less dense environment is consistent with earlier studies for eg. (Fisher & Drory 2011) where pseudo bulges and discs were found to be more dominant in under dense void like environments as compared to galaxy clusters. We also have found that bulge absolute magnitude which is an intrinsic property of the bulge does not depend on environmental density. Thus it might be likely that the processes which form and grow pseudo bulges are independent of environment and are governed by internal processes only.

However, while interpreting our results one should keep in mind the fact that bulge type is dependent on a number of parameters such as galaxy stellar mass, SFR, sSFR, morphology etc. Hence, to correctly determine the effect of environment on distribution of bulge types, one needs to separate any effect from these parameters on which bulge type depends, as they might be contributing indirectly to some extent in the observed trends. Stellar mass and a number
of parameters such as sSFR, SFR etc. are well correlated. Therefore, checking for any indirect effect of stellar mass that may show up in trend of pseudo bulges with environmental density, takes care of other quantities which are well correlated to the stellar mass. Indirect effect of other parameters such as morphology etc. on environmental dependence of pseudo bulges, have not been specifically checked in this work.

Finally, we would like to remind the reader about the sample bias. From Figure 4 we know pseudo bulges are more commonly found in galaxies having stellar mass < 10^9.5 M_☉, but as shown in Figure 3 number of such galaxies are very less in our sample. As a result, we have less number of pseudo bulges in our sample than one would expect in this mass range. Therefore, the results presented in this work on pseudo bulge fraction should be understood keeping the sample bias in mind.

In future, we would like to explore properties of pseudo bulges and their dependence on environment as well on morphology in greater detail. Using Galaxy Zoo data (Lintott et al. 2011) which provides us with morphological information on nearly 900,000 galaxies in combination with information on group properties from Yang et al. (2007), we will be able to explore many aspects of environmental secular evolution. Our result shows that the pseudo bulge fraction seems to be dependent on distance of galaxy from the group centre with lower fraction of pseudo bulges found in central galaxies as compared to satellites. With a large sample of galaxy groups, it will be possible to explore dependence of pseudo bulge fraction on the group centric distance of member galaxies. Dividing the group centric distance into different bins, one can also check dependence of pseudo bulge fraction on environment for the galaxies which are nearer and farther away from the galaxy group centre. Morphological information on large number of galaxies will also help us to separate dependence of pseudo bulge fraction on galaxy morphology which might be contributing to some extent on environmental dependence of pseudo bulge fraction. We believe that work in these directions will help to understand secular evolution in a quantitative way.

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