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A SPITZER STUDY OF PSEUDOBULGES IN S0 GALAXIES - SECULAR EVOLUTION OF DISKS

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ABSTRACT

In this Letter, we present a systematic study of lenticular (S0) galaxies based on mid-infrared imaging data on 185 objects taken using the Spitzer Infra Red Array Camera. We identify the S0s hosting pseudobulges based on the position of the bulge on the Kormendy diagram and the Sérsic index of the bulge. We find that pseudobulges preferentially occur in the fainter luminosity class (defined as having total K-band absolute magnitude M_K fainter than -22.66 in the AB system). We present relations between bulge and disk parameters obtained as a function of the bulge type. The disks in the pseudobulge hosting galaxies are found to have distinct trends on the $r_e - r_d$ and $\mu_d(0) - r_d$ correlations compared to those in galaxies with classical bulges. We show that the disks of pseudobulge hosts possess on average a smaller scale length and have a fainter central surface brightness than their counterparts occurring in classical bulge hosting galaxies. The differences found for discs in pseudobulge and classical bulge hosting galaxies may be a consequence of the different processes creating the central mass concentrations.

Subject headings: galaxies: photometry — galaxies: formation — galaxies: fundamental parameters

1. INTRODUCTION

Bulges are a central piece of the puzzle of galaxy formation and evolution. Recent work - theoretical and observational - has revealed that bulges come in two flavors: those thought to have formed through violent processes such as hierarchical clustering or major mergers and referred to as "classical bulges" and those thought to have formed through secular processes and referred to as "pseudobulges" (Kormendy & Kennicutt 2004). Many studies have been carried out proposing and examining various criteria for identifying these two classes and distinguishing between them. For example, Carollo, Stavielli & Mack (1998) identify pseudobulges based on the presence of nuclear structure as seen in images taken using the Hubble Space Telescope. Fisher & Drory (2008) employed a similar method and proposed a classification of bulges into "classical" and "pseudo" based on the Sérsic index of the bulge. Carollo et al. (2001) find a difference in the average optical-near-infrared $V-H$ color of the two kinds of bulges. The two types exhibit different behavior on various well known correlations between the structural parameters of the galaxy. The studies also show a smooth (rather than sharp) transition from one type of bulge to the other, possibly implying the existence of bulges with a mixture of properties (Gadotti 2009; Fisher & Drory 2010).

The above studies have focussed on bulge dichotomy using samples comprising of all galaxy types with a bulge and a disk but it can also be interesting to study this dichotomy within the same morphological class. In the present work, we consider S0 galaxies which form an intermediate transition class between ellipticals and spiral galaxies on the Hubble tuning fork diagram (Hubble 1936). Recent studies hint at existence of subpopulations within S0 galaxies, with different properties and formation histories. Barway et al. (2007, 2009, 2011) have proposed a divison of S0 galaxies into bright and faint classes using a dividing K-band absolute magnitude of -24.5 in the Vega system. The properties and behavior with respect to various well known correlations between morphological parameters are different for the two classes. For example, Barway et al. (2007) find a strong positive correlation between the bulge effective radius r_e and the disk scale length r_d for fainter galaxies while a weak anti-correlation is found in the case of bright galaxies. Barway et al. (2009) report distinct trends for bright and faint S0s on correlations such as the Kormendy relation, the photometric plane etc. The differences can be interpreted as the dependence of the formation history of the galaxies on the luminosity and the environment of the galaxies: the more luminous S0 galaxies should have formed through more violent processes while the faint ones through secular evolution.

If pseudobulges in S0 galaxies have formed through processes wherein the disk material rearranges itself to form the bulge, it is expected that the disk itself undergoes a change in its properties when giving rise to the bulge. In this Letter, we have carried out a mid-infrared study of a large sample of S0 galaxies to examine the properties of the bulges and the host disks. The Letter has been organised as follows. Section 2 describes the sample selection and the data. Section 3 describes the various results found and Section 4 summarises the findings and their implications. Throughout this Letter, we have assumed the standard concordance cosmology i.e. $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$.

2. SAMPLE AND DATA ANALYSIS

To assemble a statistically significant sample of S0 galaxies, we started with the RC3 catalogue (de Vaucouleurs 1991) and identified all galaxies classified as S0 (with numerical Hubble stage $-3 \leq T \leq 0$). The RC3 contains 3657 such galaxies. We impose a magnitude cut with total apparent B magnitude $B_T < 14.0$ which reduces the sample size to 1031 galaxies. For these galax-

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ies, we obtained the total apparent K_s magnitudes from the 2MASS (Two Micron All Sky Survey) All Extended Source Catalogue and converted these to absolute magnitudes using redshifts obtained from the NASA Extragalactic Database (NED)[3].

The mass content of a galaxy is dominated by low mass stars and radiation at infrared wavelengths takes into account their contribution and is also relatively free from effects of dust extinction. It is therefore appropriate to use data at near- or mid-infrared wavelengths for the study of galaxy morphology. We used the imaging data at 3.6 microns taken using the Infra Red Array Camera (IRAC) on board the Spitzer Space Telescope. IRAC offers deep images at mid-infrared wavelengths free from the problems of sky emission that plague ground based observations.

We crossmatched the above magnitude limited sample with the data available in the Spitzer Heritage Archive (SHA)[4] and found that imaging data for 247 galaxies was available. Spitzer takes dithered observations of the extended objects, which were downloaded from the SHA and coadded to a final mosaic using the MOsaicking and Point EXtraction (MOPEX) tool provided by the Spitzer Science Centre. MOPEX performs the necessary preprocessing steps which include accounting for optical distortions, image projection and outlier pixel rejection to create a final science mosaic.

In order to derive the structural parameters of various galaxy components, we employed the technique of 2-dimensional decomposition of galaxy light. We used the program GALFIT (Peng et al. 2002) for this purpose. In the first run, we fitted all galaxies with a bulge and a disk component using a Sérsic (Sérsic 1968) and an exponential profile respectively. For galaxies where the residual image obtained by subtracting the Point Spread Function convolved best-fit model from the observed image revealed a bar, a second run of fitting was performed by adding another Sérsic component to describe the bar. The bulge properties thus determined are free from the systematics that arise if a bar which is present remains unaccounted (Gadotti 2008, Laurikainen et al. 2005). During the course of the decomposition, galaxy images with poor signal-to-noise ratio and/or complicated morphological features such as tidal tails due to recent mergers were discarded from the sample. The final sample comprises of 185 galaxies with a median redshift of ~ 0.005 and a standard deviation of ~ 0.002. Further, the sample size is limited only by the availability of good quality data for non-interacting / undisturbed S0s in the SHA. The S0s were classified as bright and faint following the criterion by Barway et al. (2007, 2009, 2011), who proposed a dividing Vega magnitude of -24.5 on the 2MASS K_s absolute magnitude scale for this purpose. We transformed this division line to the AB system using $K_s(AB) = K_s(Vega) + 1.84$ as suggested by Muñoz-Mateos et al. (2009). The sample comprises of 37 bright and 148 faint galaxies as determined using the new dividing magnitude of -22.66.

[3] http://ned.ipac.caltech.edu/

[4] The Spitzer Heritage Archive is maintained by the Spitzer Science Centre and is a public interface to all archival data taken using the three instruments on board the Spitzer Space Telescope. URL : http://irsa.ipac.caltech.edu/applications/Spitzer/SHA/

We have used the AB magnitude system (Oke & Gunn 1983) throughout this Letter and where necessary, magnitudes obtained from various catalogues have been transformed to this system.

3. PSEUDOBULGES IN S0 GALAXIES

3.1. *Identifying Pseudobulges*

Fisher & Drory (2008) classified as pseudobulges those bulges which had the presence of nuclear spiral arms, bars and/or rings as seen in the high resolution near V - band images taken using the Hubble Space Telescope (see also Carollo, Stiavelli & Mack 1998). The rest were classified as classical bulges. They found that classical bulges have Sérsic index $n > 2$ and follow the same relations between various structural parameters as elliptical galaxies. But these relations were not obeyed by the pseudobulges which are found to have $n < 2$.

It appears from above that the Sérsic index can be used to classify the bulges into the two types, classifying the bulges with $n < 2$ as pseudobulges and those with $n > 2$ as classical. If we use this criterion to classify the bulges of the S0 galaxies in our sample into these two types, we have 111 classical bulges and 74 pseudobulges. Only a small fraction (13/74) of pseudobulges belong to the bright S0s with the rest (61/74) being associated with faint galaxies. However, the typical error bars on n can be quite significant. Our experience with various data shows that this error can be as large as 20% while Gadotti (2008) reports errors as large as 0.5. The parameters of the Sérsic profile n and r_e are coupled which leads to an additional uncertainty in n (see Trujillo et al. 2001 and references therein) . Thus classifying bulges using n *alone* can lead to ambiguity.

Following Fisher & Drory (2008), we tried to use high resolution HST images for constraining the classification of the bulges by searching for evidence of nuclear structure. For our S0 sample, high resolution HST imaging data were available for only 110 of the 185 galaxies in various optical bands. In the absence of a homogeneous sample of HST images, it was not possible to impose constraints using this method.

A different approach used by Gadotti (2009), which avoids the difficulties associated with using n alone, involves classifying bulges based on their position on the Kormendy diagram (Kormendy 1977). This is a plot of the average surface brightness of the bulge within its effective radius $\langle \mu_b(< r_e) \rangle$ against the logarithm of the effective radius r_e. The elliptical galaxies are known to obey a tight, linear correlation on this diagram. Classical bulges resemble elliptical galaxies and obey a similar relation while pseudobulges lie away from it. Any bulge which deviates by more than 3 times the rms (root mean square) scatter from the best-fit relation for ellipticals is classified as a pseuodobulge by Gadotti (2009).

The Kormendy plot for our sample is shown in Figure 1 with filled and empty circles respectively denoting bright and faint galaxies. Since the classification of a bulge depends on its deviation from a best-fit line to the ellipticals, the decomposition data from a study by Khosroshahi et al. (2000), of Coma cluster ellipticals done in the K-band, was used for comparison with our data. The magnitudes were transformed to the 3.6 micron band using the relation $K - m_{3.6} = 0.1$ (Toloba et al.

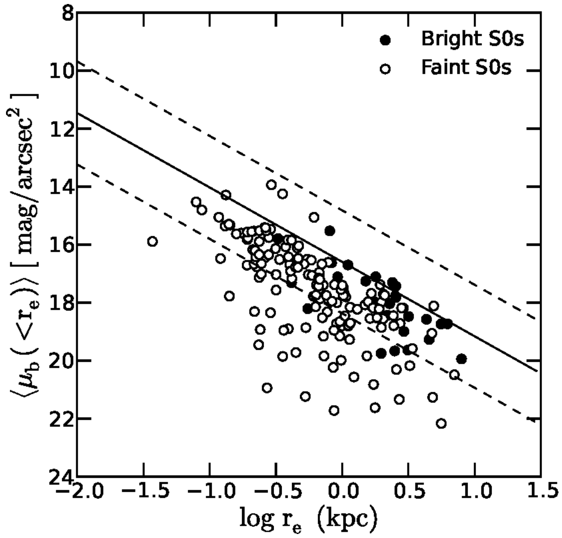

FIG. 1.— Kormendy relation with filled and open circles representing bright and faint S0s respectively. The solid line is the best-fit line to Coma cluster ellipticals while the dashed lines mark the 3-σ limits.

2012, Falcón-Barroso et al. 2011) and to the AB magnitude system by adding 1.84 following Muñoz-Mateos et al. (2009). The best-fit line for these ellipticals is

$$\langle \mu_{\rm b}(<{\rm r_e})\rangle = (2.567 \pm 0.511)\ \log\ {\rm r_e} + 16.595 \pm 0.296.$$

The rms scatter in $\langle \mu_{\rm b}(<{\rm r_e})\rangle$ for the Coma cluster ellipticals is 0.592. The best-fit line is shown in Figure 1. The dashed lines in the diagram enclose a region where all points within three times the rms scatter can be found. Following Gadotti (2009), points below this region can be classified as pseudobulges and there are 50 such points.

Interestingly, most pseudobulge hosting S0s thus classified are faint. Only three of the 37 bright galaxies are classified as pseudobulge hosts based on their position on the Kormendy diagram. If we assume that both bright and faint S0s have the same fraction (32%) of pseudobulges, we can estimate the probability of finding only three pseudobulges among bright S0s using the binomial distribution. This probability is found to be $\sim 10^{-4}$ suggesting that it is highly unlikely that bright and faint galaxies have the same chance of hosting a pseudobulge.

A set of prescriptions have been suggested by Kormendy & Kennicutt (2004) to put constraints on the bulge classification. The more constraints a bulge satisfies, the more secure its classification becomes. Apart from examing HST images for various nuclear structures, one could investigate the $\rm D_n(4000)$ indices (Gadotti 2009) to check for recent star formation as pseudobulges are known to contain a recently formed stellar population and may even be forming stars actively. However, $\rm D_n(4000)$ measurements, which are obtainable from the Sloan Digital Sky Survey (SDSS) data products are again not available for a large fraction of the S0 galaxies in our sample. The SDSS is constrained to a specific portion of the sky while our sample is an all-sky sample.

In the absence of the above indicators to have more secure classification of bulges in our S0 sample, we chose to impose a cut off on the Sérsic index n for the pseudobulge candidates obtained from the Kormendy diagram as explained above. We accept as a pseudobulge only those bulges which lie below the 3σ line and have $n < 2$. This reduces the final sample of pseudobulges to 27 (of which two are bright). All other bulges are classified as "classical". Where available, we have used HST images to confirm the presence of nuclear structure in these galaxies. Further, wherever possible, we have checked HST images of those galaxies classified as classical bulge hosts and verified that these galaxies do not show any nuclear features. We believe that our pseudobulge identification is reasonably secure. The subsequent sections are based on this sample of 27 pseudobulges and 158 classical bulges.

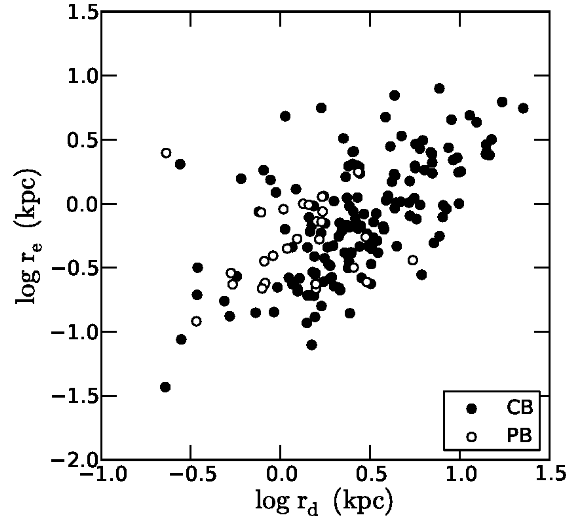

FIG. 2.— A plot of $\rm r_e$ vs $\rm r_d$ with filled and empty circles denoting classical bulges (CB) and pseudobulges (PB) respectively.

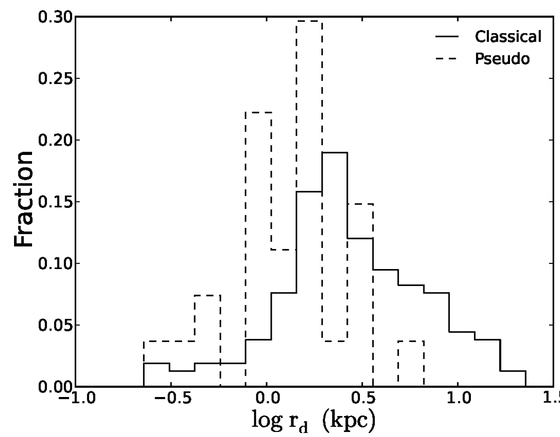

FIG. 3.— A scaled histogram showing the distribution of $\log \rm r_d$. The solid and dotted lines represent distributions for classical and pseudobulges respectively.

3.2. *Disk Correlations as Function of Bulge Type*

If pseudobulges are formed by processes within the disk, one expects a correlation between the bulge and disk scale lengths (Courteau et al. 1996), which is predicted by secular bulge formation models (Martinet 1995; Combes 2000; see Carollo et al. 1999 for comprehensive review articles). Also, one expects an imprint of the pseudobulge formation processes on correlations involving disk parameters.

In Figure 2 we plot bulge effective radius r_e as a function of the disk scale length r_d. The filled and empty circles respectively denote classical bulge hosting S0s and pseudobulge hosts. The empty circles denoting the pseu-

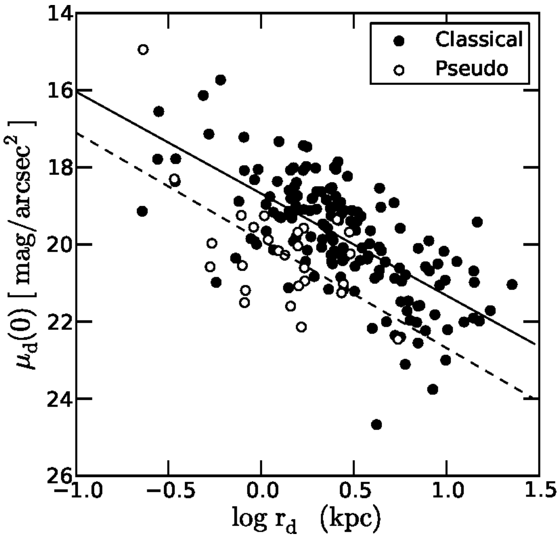

FIG. 4.— A plot of disk central surface brightness as a function its scale length. The filled and empty circles represent the classical and pseudobulges respectively. The best-fit straight lines to them are the solid and the dashed lines.

dobulge hosts are shifted towards the left relative to the filled circles which represent classical bulges. This indicates that the disk scale length is smaller on average for pseudobulge hosts than classical bulge hosts. This can be seen in Figure 3. The mean disk scale length for pseudobulge hosts is 1.6 kpc while that of classical bulges is 4 kpc. A *t-test* rules out at greater than 99.9% confidence, the possibility of this difference arising from random chance alone. This indicates that pseudobulges preferentially occur in smaller disks. The nature of the bulge depends on the formation history, in particular on whether the bulge is a product of a process such as a major merger or whether it has formed from secular evolution. If we assume that there is no reason to believe that only galaxies with larger disks should undergo such a merger it might be possible that the lower scale length of the disk in the case of a pseudobulge is due to the processes within it that grew the bulge.

If secular processes that grow pseudobulges leave behind an imprint on the progenitor disks, one should be able to find them on correlations involving disk parameters. In Figure 4, we plot the central surface brightness of the disk μ_d (0) as a function of r_d. A correlation overall is seen, with fainter central brightness corresponding to a larger disk scale length, but there is a clear offset between disks of pseudobulge hosts and those of classical bulge hosts. For a given r_d, the disk hosting a pseudobulge is fainter than the one hosting a classical bulge.

We have performed two-sample Kolmogorov-Smirnov tests to compare the distributions of central surface brightness, absolute magnitude of disk and r_d for classical and pseudobulge hosting S0s. We find that these samples of classical bulge hosts and pseudobulge hosts could not have been drawn from the same parent population, with at least 99.9% confidence.

In his paper, Gadotti (2009) finds that the disks of pseudobulge hosts are more extended and have a fainter surface brightness compared to those of classical bulge hosts but the overlap of the two kinds of galaxies is significant. It is important to note that Gadotti (2009) focusses on bulge dichotomy for a sample comprising of a mixture of different morphological types while our sample comprises of S0s alone.

4. DISCUSSION

We have presented the first systematic study of pseudobulges in S0 galaxies with emphasis on signatures of their evolutionary processes on their progenitor disks. We use the position of the bulge on the Kormendy diagram as an initial classification criterion for determing the nature of the bulge. To make our classifications more secure we have *also* used the criterion proposed by Fisher & Drory (2008) which involves using a division line of $n = 2$ on the Sérsic index scale. There are 27 pseudobulges in our sample of which two belong to bright S0s. Thus pseudobulges occur preferentially in fainter galaxies ($M_K > -22.66$, AB system). Using plots between bulge effective radius vs disk scale length and disk central surface brightness vs disk scale length, we demonstrate that distinct trends are followed by classical and pseudobulge host S0 galaxies.

The disks of pseudobulge hosting S0s have on average smaller scale lengths, lower central surface brightness and luminosity. One can either interpret this as pseudobulges preferentially occurring in a different population of disks or that these signatures are an imprint of the processes that drove the pseudobulge growth. It is not clear how to explain this finding using one of the known mechanisms for pseudobulge formation. For example, transforming a spiral with a pseudobulge via ram pressure stripping (Abadi et al. 1999) can perhaps cause disk fading but may not cause a change in the scalelength resulting in the lower r_d reported here. Perhaps a combination of processes may be able to explain the findings reported in this Letter.

In a future work, we will present a study of the current sample in greater detail and search for further signatures of the underlying processes involved in bulge and pseudobulge formation in S0 galaxies.

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[5] http://vo.iucaa.ernet.in/∼voi/AstroStat.html