

Near-Infrared bulge-disk correlations of lenticular galaxies

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3 June 2010

ABSTRACT

We consider the luminosity and environmental dependence of structural parameters of lenticular galaxies in the near-infrared K band. Using a two-dimensional galaxy image decomposition technique, we extract bulge and disk structural parameters for a sample of 36 lenticular galaxies observed by us in the K band. By combining data from the literature for field and cluster lenticulars with our data, we study correlations between parameters that characterise the bulge and the disk as a function of luminosity and environment. We find that scaling relations such as the Kormendy relation, photometric plane and other correlations involving bulge and disk parameters show a luminosity dependence. This dependence can be explained in terms of galaxy formation models in which faint lenticulars ($M_T > -24.5$) formed via secular formation processes that likely formed the pseudobulges of late-type disk galaxies, while brighter lenticulars ($M_T < -24.5$) formed through a different formation mechanism most likely involving major mergers. On probing variations in lenticular properties as a function of environment, we find that faint cluster lenticulars show systematic differences with respect to faint field lenticulars. These differences support the idea that the bulge and disk components fade after the galaxy falls into a cluster, while simultaneously undergoing a transformation from spiral to lenticular morphologies.

Key words:

galaxies: elliptical and lenticular - fundamental parameters galaxies: photometry - structure - bulges galaxies: formation - evolution

1 INTRODUCTION

Lenticular (S0) galaxies were originally conceived as a morphological transition class between ellipticals and early-type spirals by Hubble (1936). These galaxies have disks spanning a wide range in luminosity, contributing between five to fifty percent of the total galaxy light. They are distinguished from spiral galaxies by the lack of conspicuous spiral arms. For these reasons, lenticulars can be thought of as a population which is intermediate between ellipticals and early type spirals. Indeed, the placement of lenticulars by Hubble (1936) on the tuning fork diagram clearly implies such a relationship. In several observable properties such as bulge-to-disk luminosity ratio, star formation rate and colour, lenticulars are, on average, intermediate between ellipticals and early type spirals.

Detailed study of individual lenticular galaxies indicates that the situation is more complex in reality. It has been suggested (van den Bergh 1994) that there are different, but overlapping, sub-populations amongst the lenticulars. Exploration of formation sce-

narios for lenticulars using theory and numerical simulations also suggest that lenticulars may have formed in different ways. They could be of primordial origin forming rather rapidly at early epochs, or could have been formed by the slow stripping of gas from spirals, which changes the morphology (Abadi, Moore & Bower 1999), or through the mergers of unequal-mass spirals (Bekki 1998). The two main components of lenticulars – the bulge and the disk – may have their own *different* and possibly *independent* formation history. Observationally, the disks seem to be younger than the bulges in both spiral and lenticular galaxies (Peletier & Balcells 1996), with the age difference between the two components larger in lenticulars (Bothun & Gregg 1990). Bars in lenticular galaxies are also of interest in many studies as they provide a clue about the evolutionary history of these galaxies. Recent studies reveal that bars in lenticular galaxies are shorter, less massive and have smaller bar torques (Buta et al. 2006; Laurikainen et al. 2005; Laurikainen et al. 2006; Gadotti, D. A. et al. 2007).

A detailed multiband study of the morphology of representative samples of lenticulars in different environments, and comparison of their properties with those of ellipticals, and with bulges

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Table 1. Best fit Bulge and Disk parameters for our sample.

Name	z	T	Bulge parameters				Disk parameters			B/T	M_T
			$\mu_b(0)$ (mag arcsec $^{-2}$)	r_e (kpc)	n	e_b	$\mu_d(0)$ (mag arcsec $^{-2}$)	r_d (kpc)	e_d		
UGC 00080	0.01019	-3	11.54	0.45	1.63	0.001	15.69	2.33	0.505	0.19	-24.99
UGC 00491	0.01664	-1	10.38	4.95	3.82	0.257	17.65	5.08	0.231	0.65	-25.53
UGC 00859	0.00711	0	11.34	1.39	3.36	0.141	16.40	1.22	0.403	0.43	-23.25
UGC 00926	0.01467	-2.5	09.74	9.81	4.39	0.348	14.93	0.80	0.353	0.93	-26.17
UGC 01250	0.01235	-2	09.51	1.92	3.79	0.397	15.92	2.66	0.696	0.32	-25.24
UGC 01823	0.01332	-3	11.41	1.96	2.28	0.416	16.81	6.56	0.398	0.34	-26.34
UGC 01964	0.01732	-2	10.06	4.03	3.96	0.103	15.60	1.86	0.585	0.58	-25.33
UGC 02039	0.01505	-2	10.18	1.92	3.37	0.007	17.19	5.52	0.644	0.29	-25.52
UGC 02187	0.01605	-2	13.11	0.45	0.76	0.276	15.13	1.99	0.554	0.14	-25.17
UGC 02322	0.01447	-1	10.51	4.18	3.86	0.008	16.84	2.08	0.015	0.75	-24.89
UGC 03178	0.01578	-2	09.84	2.55	3.89	0.014	14.76	1.17	0.479	0.47	-24.90
UGC 03452	0.01876	-2	10.53	3.31	3.47	0.242	15.91	2.89	0.516	0.46	-25.70
UGC 03536	0.01564	-2	13.18	0.55	0.99	0.012	14.80	2.03	0.576	0.10	-25.48
UGC 03567	0.02016	-2	09.96	4.87	4.15	0.062	15.99	1.06	0.503	0.87	-25.04
UGC 03642	0.01500	-2	11.94	1.03	2.02	0.010	17.74	8.45	0.206	0.17	-25.72
UGC 03683	0.01908	-2	12.13	1.56	1.83	0.283	17.01	5.69	0.171	0.37	-25.91
UGC 03699	0.01947	-2	10.35	3.13	3.32	0.336	16.54	1.65	0.489	0.87	-25.36
UGC 03792	0.01908	0	10.17	4.41	3.74	0.224	18.15	5.71	0.225	0.72	-25.66
UGC 03824	0.01787	-2	11.40	1.52	2.71	0.003	17.43	3.18	0.002	0.52	-24.52
UGC 04347	0.01494	-2	10.68	4.33	3.34	0.243	16.34	1.01	0.528	0.95	-25.57
UGC 04767	0.02413	-2	09.05	7.65	4.74	0.105	14.98	0.27	0.001	0.99	-25.55
UGC 04901	0.02810	-2	13.30	3.06	1.78	0.305	18.08	14.28	0.043	0.27	-26.70
UGC 05292	0.00511	-2	09.22	0.26	3.08	0.008	17.28	2.01	0.282	0.21	-23.07
UGC 06013	0.02190	-2	11.29	5.10	3.68	0.325	15.41	1.00	0.001	0.78	-24.89
UGC 06389	0.00663	-2	11.71	3.00	3.36	0.378	13.88	0.21	0.334	0.89	-23.75
UGC 06899	0.02249	-2	09.79	5.11	4.06	0.060	16.71	0.53	0.001	0.99	-25.35
UGC 07142	0.00328	-2	10.48	0.35	2.22	0.219	15.96	1.32	0.503	0.33	-23.66
UGC 07473	0.00414	-2	11.76	0.24	1.20	0.239	14.55	1.20	0.725	0.12	-24.57
UGC 07880	0.00388	-3	11.50	0.68	2.39	0.330	14.29	0.63	0.747	0.34	-23.74
UGC 08675	0.00361	-2	09.18	0.25	3.35	0.020	17.14	1.48	0.011	0.19	-22.53
UGC 09200	0.01081	-2	12.33	1.35	2.23	0.117	17.83	3.10	0.001	0.57	-24.15
UGC 09592	0.01791	-2	08.69	1.62	3.62	0.315	16.30	2.33	0.123	0.65	-25.30
UGC 11356	0.00820	-2.5	11.64	0.47	1.64	0.080	15.16	1.46	0.020	0.24	-24.57
UGC 11972	0.01463	-2.5	10.29	8.62	4.08	0.441	14.24	0.45	0.002	0.95	-26.00
UGC 12443	0.01463	-2	10.83	3.34	3.44	0.097	19.36	0.04	0.002	1.00	-24.61
UGC 12655	0.01727	-2	10.34	1.14	2.87	0.191	16.86	4.77	0.400	0.24	-25.47

Notes. Column (1) gives the UGC catalogue number, column (2) and column (3) give redshift and morphological type respectively from NED, columns (4), (5), (6) and (7) give unconvolved bulge central surface brightness, bulge effective radius, Sérsic index and bulge ellipticity respectively, columns (8) (9) and (10) give unconvolved disk central surface brightness, disk scale length and disk ellipticity respectively, column (11) gives the bulge-to-total luminosity ratio and column (12) gives the absolute magnitude in the K band.

and disks of spirals will be important in addressing these issues observationally. However, comparing the predictions of models to observations is complicated for two main reasons: (1) The models often use simplifying assumptions that may not hold for real galaxies and (2) Models often do not make firm predictions about *directly observable* quantities. Nevertheless, the *statistical* properties of galaxy ensembles can be compared to model predictions. Such a quantitative comparison between bulge and disk properties of galaxies is considerably simplified if one assumes simple analytic profiles for the light distribution of the bulge and the disk. In practice, the Sérsic $r^{1/n}$ law (Sérsic 1968) adequately represents the bulge surface brightness distribution while an exponential best represents the disk surface brightness distribution. The total galaxy light is simply the sum of a Sérsic bulge and an exponential disk.

In this work, we obtain and report structural parameters for 36 lenticular galaxies observed in the near-infrared K band. Us-

ing results from the bulge-disk decomposition, we examine correlations among the bulge and disk parameters and discuss implications to models of lenticular formation. Our goal is mainly to study the constraints placed on bulge formation in lenticular galaxies by these parameter correlations. Specifically, we want to investigate, in greater detail, the discovery of Barway et al. (2007) who found two distinct populations of bulges in lenticulars that were fainter and brighter than a threshold luminosity.

This paper is organised as follows: the sample, details of near-infrared observations, data reduction technique and photometric calibration are summarised in § 2. The two-dimensional decomposition analysis is described in § 3. In § 4, we discuss the luminosity and environment dependence of lenticular galaxy properties.

Throughout this paper, we use the standard concordance cosmology with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and $h_{100} = 0.7$.

2 OBSERVATIONS AND DATA REDUCTION

2.1 Our sample

Our sample consists of a set of 36 bright field lenticular galaxies from Barway et al. (2005). The original sample contained 40 lenticulars galaxies, selected from the Uppsala General Catalogue (UGC), with apparent blue magnitude brighter than $m_B = 14$, diameter $D_{25} < 3$ arcmin and declination in the range $5 < \delta < 64^\circ$. The sample, while not complete, is representative of bright field lenticulars.

We obtained images of the sample galaxies in the near infrared K band with the *Observatorio Astronomico Nacional* 2.1-m telescope at San Pedro Martir, Mexico. The CAMILA instrument (Cruz-Gonzalez et al. 1994), which hosts a NICMOS 3 detector of 256×256 pixel format, was used in the imaging mode. Each K band observing sequence consisted of 10 exposures, six on the object and four on the sky. The net exposure times were, typically, 10 minutes per galaxy. A series of twilight and night-sky images were taken for flat-fielding purposes. The K observations were carried out in four runs in December 2000, March 2001, October 2001 and March 2002. The data reduction procedure for the K images involved subtraction of the bias and sky frames, division by flat field frames, registration of the images to a common co-ordinate system and then stacking of all the images of a given galaxy. All image reductions were carried out using the Image Reduction and Analysis Facility (IRAF¹) and the Space Telescope Science Data Analysis System (STSDAS²). Standard fields were observed in order to enable accurate photometric calibration of our K band observations. Reddening corrections due to Galactic extinction and K-correction were applied to individual galaxies. Full details on sample selection, observation, and data reduction procedures can be found in Barway et al. (2005).

2.2 Comparison samples

We supplement our sample with data from Bedregal et al. 2006 (hereafter BAM06) and additional data provided by Bedregal & Aragón-Salamanca in electronic form (private communication) who used the Two Micron All Sky Survey (2MASS; Jarrett et al. 2003) data for a structural analysis of a sample of 49 lenticular galaxies. These are relatively faint objects with sufficient rotational support for the disks. Addition of these data complements our sample in two ways: (a) it provides a low luminosity extension to the galaxies in our sample and (b) it provides lenticulars in different environments i. e., galaxies from the Coma (14 galaxies), Virgo (8 galaxies), and Fornax (6 galaxies) clusters along with 21 field lenticulars. Whenever a comparison with other morphological classes is appropriate, we have used results from analyses of the following samples:

- A sample of 42 elliptical galaxies from the Coma cluster observed in K band by Mobasher et al. (1999) as analysed by Khosroshahi et al. (2000b).
- A sample of 26 early type spiral galaxies in the field observed

by Peletier & Balcells (1997) in the K band as analysed by Khosroshahi et al. (2000b).

- A sample of 40 late-type spiral galaxies observed and analysed by Möllenhoff & Heidt (2001) in the K band.

All the above analyses model the galaxy light using the Sérsic function for the bulge and an exponential function for the disk. In all cases, the bulge-disk decomposition is performed using the full 2D image of the galaxy. Incidentally, for all samples except that of BAM06 and Möllenhoff & Heidt (2001), the decomposition has been performed with the same code *fitgal* (Wadadekar et al. 1999). Details of the sample selection, observation, data reduction and bulge-disk decomposition of these samples may be found in the references cited.

3 ANALYSIS

3.1 2-d image decomposition

Extracting the structural parameters of a galaxy requires the separation of the observed light distribution into bulge and disk components. There is considerable variation in the details of the decomposition techniques proposed by various researchers. In recent years, methods that employ two dimensional fits to broad band galaxy images have become popular (e. g. Wadadekar, Robbason & Kembhavi 1999; Peng et al. 2002; Simard et al. 2002; de Souza et al. 2004). Most of these decomposition techniques assume specific surface brightness distributions like the Sérsic law for the bulge and an exponential distribution for the disk.

Our decomposition procedure is a full two dimensional method that uses information from all pixels in the image. *fitgal* essentially involves a numerical solution to a signal-to-noise (hereafter S/N) weighted χ^2 minimisation problem. We achieve this minimisation using the Davidon-Fletcher-Powell variable metric algorithm included as part of MINUIT – a multidimensional minimisation package from CERN. Our technique involves iteratively building two dimensional image models that best fit the observed galaxy images, with the quality of the fit quantified by the χ^2 value. We compute weights for the χ^2 function using the S/N ratio at each pixel of the galaxy image. We convolve the model image with the measured point spread function from the galaxy frame before the χ^2 is computed. Details of the accuracy and reliability of the decomposition procedure as assessed by simulations, are provided in Wadadekar et al. (1999).

At near-infrared wavelengths, dust related absorption and emission from patchy star forming regions are both weak relative to optical wavelengths. The smooth, featureless light profiles of galaxies in the near-infrared are very convenient for modelling using simple analytic functions to represent the galaxy components. Use of K band data is especially important for our sample, as it includes several dusty galaxies. In our bulge-disk decomposition, we have the following quantities as free parameters: (1) $I_b(0)$: the central bulge intensity, in counts, which can later be converted to mag arcsec⁻² using the photometric calibration (2) r_e : the half light radius of the bulge in pixels (3) e_b : the ellipticity of the bulge (4) n : the bulge Sérsic index (5) $I_d(0)$: the central intensity of the disk in counts (6) r_d : the scale length of the disk in pixels (7) e_d : the ellipticity of the disk

With these definitions, the Sérsic bulge intensity distribution can be written as

$$I_{bulge}(x, y) = I_b(0)e^{-2.303b_n(r_{bulge}/r_e)^{1/n}}, \quad (1)$$

¹ IRAF is distributed by National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

² STSDAS is a product of the Space Telescope Science Institute, which is operated by AURA for NASA.

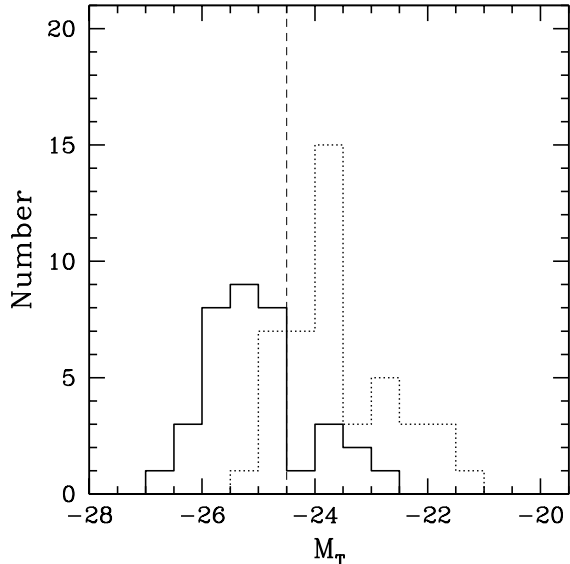


Figure 1. Distribution of total absolute magnitude (M_T) in K band for our sample (solid line) and for BAM06 lenticulars (dotted line). The vertical dashed line corresponds to total absolute magnitude $M_T = -24.5$, which we use to divide low- and high-luminosity lenticulars.

$$r_{bulge} = \sqrt{x^2 + y^2 / (1 - e_b)^2},$$

where x and y are the distances from the centre of the galaxy along the major and minor axis respectively and b_n is a function of n and the root of an equation involving the incomplete gamma function. However, following Khosroshahi et al. (2000b), b_n can be approximated as a linear function of n , accurate to better than one part in 10^5 , by

$$b_n = 0.868242n - 0.142058.$$

For $n = 4$, which corresponds to de Vaucouleurs law, $b_4 = 3.33$.

The projected disk profile is represented by an exponential distribution,

$$\begin{aligned} I_{disk}(x, y) &= I_d(0)e^{-r_{disk}/r_d}, \\ r_{disk} &= \sqrt{x^2 + y^2 / (1 - e_d)^2}. \end{aligned} \quad (2)$$

The ellipticity of the disk in the image is due to projection effects alone and is given by

$$e_d = 1 - \cos(i), \quad (3)$$

where i is the angle of inclination between the line of sight and the normal to the disk plane.

The bulge-to-disk luminosity ratio is a dimensionless parameter which is commonly used as a quantitative measure for morphological classification of galaxies. For a Sérsic bulge and an exponential disk it is given by

$$(B/D)_n = \frac{n\Gamma(2n)}{(2.303b_n)^{2n}} \left(\frac{I_b(0)}{I_d(0)} \right) \left(\frac{r_e}{r_d} \right)^2. \quad (4)$$

We use the bulge-to-total luminosity ratio $B/T = (B/D)/(1 + (B/D))$ in this paper, since it spans a restricted range of 0 to 1.

3.2 Extraction of structural parameters using 2-d image decomposition

Although the K band observations are advantageous for their relative lack of absorption related problems, the high sky background in K band poses some difficulty in extracting the global photometric parameters accurately, as it limits the region where S/N is high enough for the pixels to be usable. Even a small error in the sky estimation can lead to spurious results because of the relatively low S/N in the images. For example, if the sky is under-estimated, say by 5%, the residual background can lead to a spurious detection of a large circular disk with a non-zero $I_d(0)$. Even when a ‘bulge only’ model is used, a wrong assessment of the background can lead to serious mis-estimation of the morphological parameters.

In our K band images, the sky background is automatically subtracted from the many individual sky frames for each galaxy during the preprocessing stage (see Barway et al. 2005 for details). However, if sky is removed, noise statistics calculations at low S/N (where the sky dominates) are grossly inaccurate. To avoid this problem, we added back the sky background that had been subtracted from each galaxy image.

Our bulge-disk decomposition code *fitgal* (Wadadekar et al. 1999) allows the estimation of the background simultaneously with the estimation of morphological parameters. However, such a measurement can lead to unstable values for the parameters, as the background counts are much higher than the signal even in the central region of the galaxies. To avoid this instability, we had a run for each galaxy in which the aim was to estimate the background rather than to obtain the morphological parameters accurately. To this end, we first ran the code on a selected region of each galaxy image, dominated by the sky background. We compared the value of the background returned by the fitting procedure, with that estimated from regions of the image frames free of the galaxy and from the observed sky images to ensure that these values are all consistent with each other. We then adopted the sky value returned by the code as the best representation of the sky background, since this uses information from all the relevant pixels of the image, and fixed the background parameter to this value during all subsequent runs of *fitgal*.

We fitted ellipses to the isophotes of each galaxy of our sample, and obtained the one dimensional surface brightness profile along the major axis, using the STSDAS task *ellipse*. For this task, sky subtracted galaxy frames were used. The fits provided us with model independent surface brightness distributions, which could be compared to the surface brightness distribution predicted by our best fit bulge plus disk models. In order to obtain good initial values for our two dimensional fits, we fitted the inner part of one dimensional profiles obtained above with de Vaucouleurs law profiles (taking care to avoid the region affected by the PSF) and the outer part with the exponential law. This provided us with approximate values of $I_b(0)$ and r_e for bulge and $I_d(0)$ and r_d for disk, which we used as input to obtain a full two dimensional Sérsic and exponential model fit to each galaxy in the sample. During the fit for each galaxy, we fixed the background to the value obtained as described above. Of the 40 galaxies in our sample, we could not get satisfactory fits for three galaxies, UGC 03087, UGC 11178 and UGC 11781. UGC 03087 is a strong radio source with an optical jet visible in the image make the fit unreliable. For galaxies UGC 11178 and UGC 11781, our images suffer from poor S/N ratio and we are not able to get satisfactory fits. UGC 07933 is classified as an elliptical in the RC3 catalogue. We therefore exclude these four galaxies from subsequent discussions, leaving us with a

sample of 36 galaxies. We have listed in Table 1 the best fit bulge and disk parameters for all the 36 lenticular galaxies in the sample.

BAM06 used images in the K band from the 2MASS survey to obtain bulge and disk parameters for the 49 galaxies in their sample, using the *gim2d* decomposition code by Simard et al. (2002), assuming Sérsic and exponential laws for the bulge and disk light distributions, as we have done with our sample. Barway et al. (2007) have shown (see their Figure 2a) that there are three clear outliers among the cluster lenticulars of the BAM06 sample. Inspection of the 2MASS K band images of the corresponding galaxies, shows that one of these (ESO 358-G59) has poor S/N ratio, while the other two (NGC 4638 and NGC 4787) are obviously disk-dominated systems, which are likely to have disk scale lengths larger than those reported by BAM06. Following Barway et al. (2007), we omit these three outliers from further discussion, while noting that our conclusions are not significantly changed by this omission.

It must be noted that the depth of our K band images is considerably more than the depth of 2MASS images used by BAM06. We have a typical exposure time of 10 minutes per galaxy as opposed to 7.8 sec/frame in 2MASS. This combined with the fact that we used a somewhat larger telescope for obtaining our data allows us to reach a depth of typically $22 \text{ mag arcsec}^{-2}$, corresponding to an error in photometry of $0.1 \text{ mag arcsec}^{-2}$. The 2MASS data used by BAM06 reach a typical depth of $20 \text{ mag arcsec}^{-2}$ for the same error. This implies that our images are about 2 magnitudes deeper than the 2MASS data. Given the significant difference in typical depth, bulge disk decompositions of the low S/N 2MASS data may, in principle, be systematically affected. To probe the extent of this effect, we obtained 2MASS images for all the galaxies in our sample and performed the decomposition using our technique on these data. For 80% of galaxies, we found a reasonable match between parameters extracted from our data and the 2MASS data. For 20% of galaxies our fitting procedure failed when using 2MASS data, indicating that the low S/N was affecting our ability to extract parameters reliably for these galaxies. However, such an inability to obtain reliable fits is unlikely to affect the parameter extraction procedure of BAM06, which is based on the Metropolis algorithm (Metropolis et al. 1953), as implemented in the *gim2d* software (Simard et al. 2002). *gim2d* is a robust, albeit slow, bulge-disk decomposition software that obtains the global minimum of a fit, in almost any situation. It is thus well suited for parameter extraction for relatively shallow data like that of BAM06, where the low S/N is likely to make fitting difficult.

Another possible concern is whether a linear combination of a bulge and a disk is an adequate mathematical formulation to model the light distribution of galaxies in our sample e.g. if a significant non-axisymmetric bar (or similar structure) were present for the galaxies in our sample, that would affect the parameters that we extract (see Laurikainen et al. 2005 for a discussion on the fitting of non-axisymmetric components). It is fortunately easy to detect the presence of non-axisymmetric structure by examining the residuals of our fitting, which are computed as the difference between the galaxy image and best fit model. Since the analytic functions we use to model the bulge and disk are axisymmetric, the bars are not modeled in our scheme. They remain in the residual image, and can be visually seen if they are bright enough. For the 36 galaxies in our sample, the RC3 catalog indicates that 5 may have bars. We find from the residuals that only one galaxy (UGC 80) has a discernable bar. For the BAM06 galaxies, the RC3 catalog indicates that 14 out of 47 galaxies may have bars. We find non-axisymmetric structures in 11 of these 15 galaxies. For these galaxies, extracted parameters

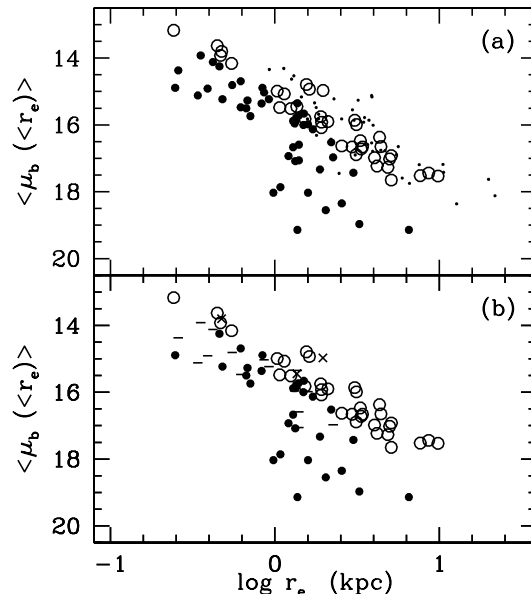


Figure 2. Dependence of the mean surface brightness within bulge effective radius ($\langle \mu_b (< r_e) \rangle$) on bulge effective radius r_e (a) for bright (as open circles) and faint lenticulars (filled circles). Coma ellipticals (as dots) are overlotted for comparison. (b) for bright lenticulars with bars (as crosses) and faint lenticulars with bars (as dashed) as classified in RC3 catalogue.

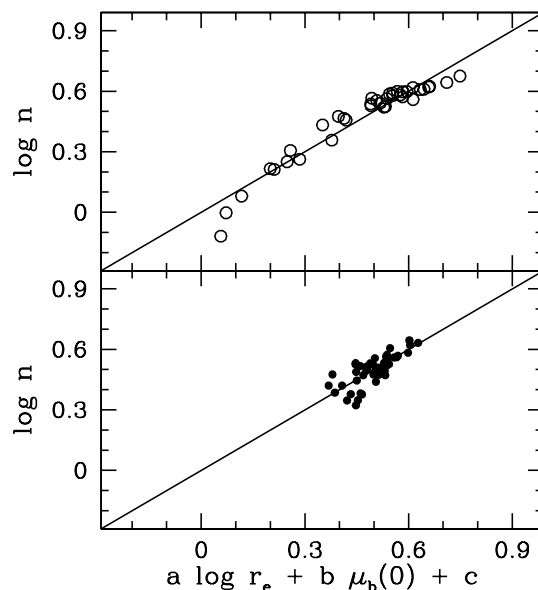


Figure 3. An edge-on view of the photometric plane (PP) for lenticulars. Top: PP for bright lenticulars; $\log n = 0.251 \pm 0.045 \log r_e - 0.094 \pm 0.012 \mu_b(0) + 1.377 \pm 0.138$. Bottom: PP for faint lenticulars; $\log n = 0.185 \pm 0.029 \log r_e - 0.041 \pm 0.004 \mu_b(0) + 0.935 \pm 0.046$.

are likely to be somewhat inaccurate. For the analysis subsequently reported in this paper, such inaccuracy is of concern only if it leads to *systematic* offsets between barred and non-barred galaxies. We demonstrate in Section 4.1.1 that such obvious systematic offsets do not exist, implying that inaccurate parameter estimation for a small fraction of galaxies will not alter the results of this work.

Table 2. photometric plane coefficients for bright & faint lenticulars.

Lenticular Sample	a	b	c	N	rms _n	rms _o
Bright	0.251±0.045	-0.094±0.012	1.377±0.138	38	0.037	0.036
Faint	0.185±0.029	-0.041±0.004	0.935±0.046	44	0.039	0.038
Bright with restricted n	0.150±0.0213	-0.056±0.007	1.050±0.067	29	0.019	0.019

Notes. a and b are the coefficients of $\log r_e$ and $\mu_b(0)$ respectively, c is the constant, N is the number of galaxies, rms_n is the r.m.s. scatter measured along the $\log n$ axis and rms_o is the r.m.s. scatter measured in a direction orthogonal to the best-fit photometric plane.

4 CORRELATIONS AND DISCUSSION

4.1 Luminosity dependence

Barway et al. (2007) have presented evidence to support the view that the formation history of lenticular galaxies depends upon their luminosity. According to this view, low-luminosity lenticular galaxies likely formed by the stripping of gas from the disk of late-type spiral galaxies, which in turn formed their bulges through secular evolution processes. On the other hand, more luminous lenticulars likely formed at early epochs through a rapid collapse followed by rapid star formation.

As we mentioned earlier, the BAM06 galaxies complement our sample in two ways: they extend to fainter luminosities and provide lenticulars in different environments. In Figure 1 we show the distribution of total absolute magnitude (M_T) in the K band for the combined sample, which is seen to span a wide range in luminosity. We divide the combined sample into faint and bright groups, using $M_T = -24.5$ as a boundary. The bright sample has 37 lenticulars while 46 lenticulars belong to the faint sample according to this luminosity division. The boundary at $M_T = -24.5$ is somewhat arbitrary but our results do not critically depend on small shifts in the dividing luminosity. For instance, changing this value by half a magnitude on either side maintains correlations significant at least at the 95% level.

Using the luminosity division at $M_T = -24.5$, Barway et al. (2007) reported markedly different correlations between bulge effective radius (r_e) and disk scale length (r_d) for bright and faint lenticulars. A positive correlation of bulge and disk sizes is expected if the bulge grows over time through secular evolution processes (see review by Kormendy & Kennicutt 2004). No such correlation is expected if the bulge formed via merger related processes. Barway et al. (2007) found this positive correlation between bulge and disk sizes of low luminosity lenticulars; such a correlation was not observed for bright lenticulars. Moreover, they found that the correlation holds for faint galaxies, irrespective of whether they are situated in a field or cluster environment.

If the differences between low and high luminosity lenticulars are indeed fundamental, then there should be systematic differences seen between the two populations in other correlations among bulge and disk parameters. We study such correlations in the following sections.

4.1.1 Kormendy relation and the effect of bars

For samples of large elliptical galaxies, the central surface brightness $\mu_b(0)$ (or, equivalently, the mean surface brightness $\langle\mu_b(< r_e)\rangle$ within r_e) is correlated with $\log r_e$. This was first reported by Kormendy (1977) and is known as the Kormendy relation. In Figure 2(a) we show the Kormendy relation for bright

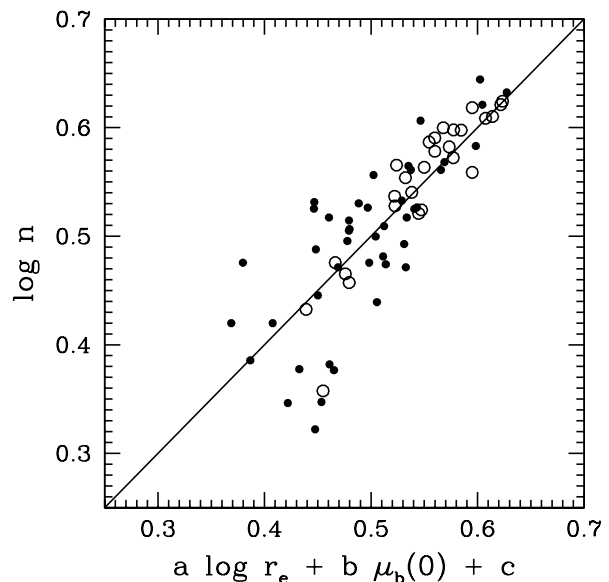


Figure 4. Photometric Plane for bright lenticulars (open circles) with restricted n value. Faint lenticulars (filled circles) are over plotted on the same photometric plane. These show a higher scatter than the bright ones.

(as open circles) and faint lenticulars (as filled circles). The bright lenticulars show tight correlation with Pearson correlation coefficient $r = 0.95$ with significance greater than 99.99%. The Kormendy relation for faint lenticulars shows considerably greater scatter although the Pearson correlation coefficient is 0.75 with significance greater than 99.99%. Figure 2(b) show the Kormendy relation for bright (as crosses) and faint (as dashes) lenticulars classified as barred lenticulars in RC3 catalogue to probe for any systematic effect caused due to presence of bars. It is clear from the figure that barred and non-barred show no systematic offset. Only three galaxies are classified as barred in our bright galaxy sample (indicated by crosses). Even after removing these three galaxies, the correlation is nearly unchanged with Pearson correlation coefficient $r = 0.96$ with significance greater than 99.99%. In the faint lenticular sample, there are as many as 16 galaxies classified as barred. Nevertheless, neglecting these 16 galaxies does not affect the correlation which has $r = 0.74$ with significance greater than 99.99%. For all other correlations subsequently reported in this paper, we find that excluding barred galaxies does not significantly alter the correlation coefficient or its significance. Hence, in further discussion, we do not differentiate between barred and non-barred lenticulars, and include both types in the analysis.

The Kormendy relation is known to be a projection of the fundamental plane (Djorgovski & Davis 1987; Dressler et al. 1987)

of galaxies. A tight Kormendy relation indicates (near) virialized bulges like those found in elliptical galaxies. In Figure 2a, ellipticals from the Coma cluster are overplotted as dots. As expected, these ellipticals show a tight correlation with Pearson correlation coefficient $r = 0.81$ with significance greater than 99.99 %. The slopes of the best-fit Kormendy relation for bright lenticulars and Coma ellipticals are similar. This similarity coupled with the systematic difference in scatter in the Kormendy relation between bright and faint lenticulars is an indicator of the more virialized state of the bright lenticular bulges and their close relation to ellipticals.

4.1.2 Photometric Plane

Analogous to the fundamental plane (FP), ellipticals and the bulges of early type spiral galaxies obey a single planar relation of the form $\log n = a \log r_e + b \mu_b(0) + c$ which Khosroshahi et al. (2000a,b) called the photometric plane (PP). Assuming that galaxy bulges behave as spherical, isotropic, one-component systems, there is a unique specific entropy that can be associated with every galaxy (Lima-Neto et al. 1999). This in turn, implies a relation between bulge parameters that is equivalent to the observed photometric plane. An edge-on view of the best-fit PP is shown in the top and bottom panels of Figure 3 for bright and faint lenticulars respectively. Table 2 lists the coefficients for best-fit PP relation. It is immediately evident from Figure 3 that the PP for faint lenticulars spans a limited range of n . We restrict our bright lenticular sample to the range spanned by the faint lenticulars and then obtain the best fit PP for this restricted sample. The rms scatter for the (restricted) bright galaxies is considerably smaller than that for the faint galaxies (see Table 2). In Figure 4 we show the PP for these two sets of galaxies. Visually, the higher scatter of the faint galaxies about the PP is obvious. The PP is a natural state for galaxies that formed like ellipticals (at early epochs in a burst of rapid star formation, with stellar orbits that are well relaxed). The fact that bulges of bright lenticulars have a tight PP is an indicator of homology with ellipticals. Faint lenticulars seem to belong to a separate class.

4.1.3 Correlations involving the Sérsic index (n)

The restricted range spanned by the Sérsic index in faint lenticular galaxies also affects other correlations involving this index. Figure 5 is a plot of the Sérsic index (n) as a function of effective radius (r_e) which again shows systematic differences between bright and faint lenticulars. Bright lenticulars are well correlated having Pearson correlation coefficient $r = 0.79$ with significance greater than 99.99 % but faint lenticulars do not show a significant correlation. A strong correlation exists between n and the bulge central surface brightness ($\mu_b(0)$), as shown in Figure 6 for the brighter lenticulars. The Pearson correlation coefficient in this case is 0.84 at a significance level better than 99.99%. Faint lenticulars also exhibit good correlation having Pearson correlation coefficient $r = 0.58$ at significance 99.96 %, but have a markedly different slope. Comparing Figure 5 and Figure 6 with Figure 3 and Figure 4 respectively of Khosroshahi et al. (2000b), we observe a close correspondence in the distribution of the bulges of *bright* lenticulars and early type spirals. Bulges of early type spirals, in turn, have a close correspondence with ellipticals (Khosroshahi et al. 2000b). On the other hand, faint lenticulars seem to be a different population.

The bulge-to-total luminosity ratio (B/T) increases with Sérsic index n as shown in Figure 7 for brighter lenticulars ($r =$

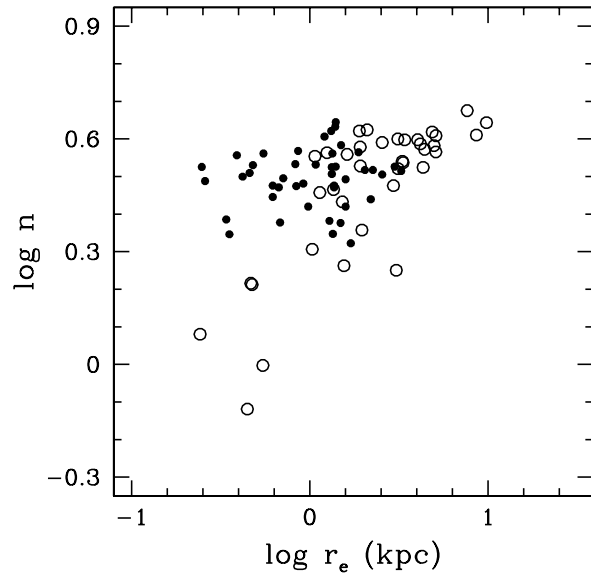


Figure 5. Sérsic index n plotted against bulge effective radius r_e in kpc. Symbols are as in Figure 2.

0.81 with significance greater than 99.99 %). Faint lenticulars show a weak correlation between $\log(B/T)$ and $\log n$. Again, the trends for bright lenticulars are consistent with those found by Khosroshahi et al. (2000b) in early-type spirals. Bright lenticulars plotted in Figure 3 of Barway et al. (2007) include 5 galaxies that are obvious outliers in the anti-correlation of bulge and disk sizes. These bright lenticulars viz. UGC 80, UGC 2187, UGC 3536, UGC 7473 and UGC 11356 do follow the correlations involving the Sérsic index. However, they are all characterised by a low Sérsic index, low bulge central surface brightness, low bulge effective radius and low bulge-to-total luminosity ratio. This places these lenticulars in the bottom left quadrant of Figures 5, 6 and 7. Their bulge/disk parameters indicate that these are disk-like systems, with relatively weak bulges, making them unlikely candidates of major merger induced formation. Nevertheless, they do follow the same correlations, involving the Sérsic index, as the other bright galaxies. This discrepancy needs to be explored with a larger sample of bright, but diskly lenticulars.

4.1.4 Disk correlations

There exist clear correlations between the two main disk parameters –central surface brightness of the disks ($\mu_d(0)$) and disk scale-length (r_d)– for both bright and faint lenticulars (see Figure 8) although they occupy different regions of the plot. Lenticulars with large disks have a lower central surface brightness, on average. A clear anti-correlation is seen between these two disk parameters for bright lenticulars but the scatter is large. The linear correlation coefficient between $\mu_d(0)$ and $\log r_d$ is 0.43 with a significance of 99.37 percent. Faint lenticulars show less scatter with the correlation coefficient of 0.70 at a significance level better than 99.99 %. Similar statistically significant correlation was reported by Khosroshahi et al. (2000b) for early-type spirals and Möllenhoff & Heidt (2001) for late-type spirals for these disk parameters. In Figure 8, we also plot as dots the central surface brightness of the disks ($\mu_d(0)$) against the disk scale length (r_d) of galaxies from the K band observations of Khosroshahi et al. (2000b) of early-type spi-

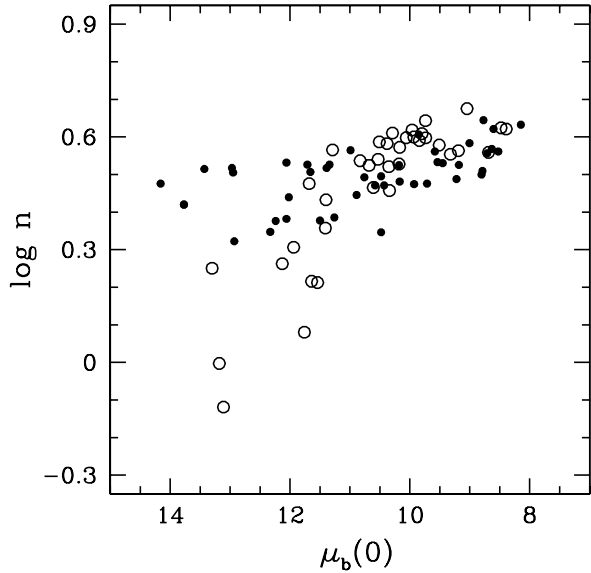


Figure 6. Sérsic Index n as a function of unconvolved bulge central surface brightness. Symbols are as in Figure 2.

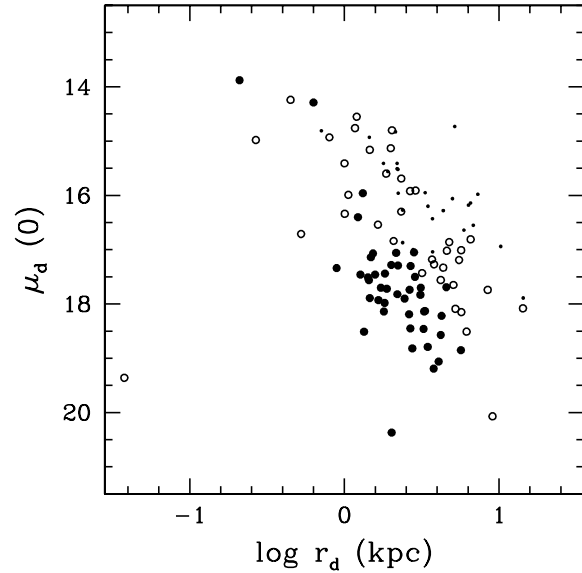


Figure 8. Unconvolved disk central surface brightness $\mu_d(0)$ as a function of disk scale length. Early-type spirals (as dots) are overplotted for comparison. Other symbols are as in Figure 2.

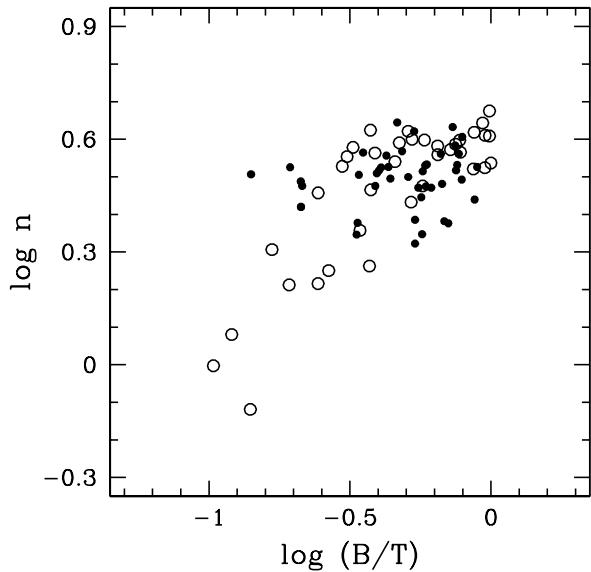


Figure 7. Sérsic Index n vs. bulge-to-total luminosity ratio. Symbols are as in Figure 2.

erals. From the plot it is apparent that the disk scale lengths of our sample and the Khosroshahi et al. (2000b) sample span the same range, but $\mu_d(0)$ are brighter, on the average, for early-type spirals than faint lenticulars.

4.2 Environmental dependence

The dependence of cluster environment on formation and evolution of galaxies is well known. The environment influence is best visible through the well-known morphology-density relationship, according to which early-type galaxies are preferentially found in rich environments (Dressler 1980), with spirals are found predom-

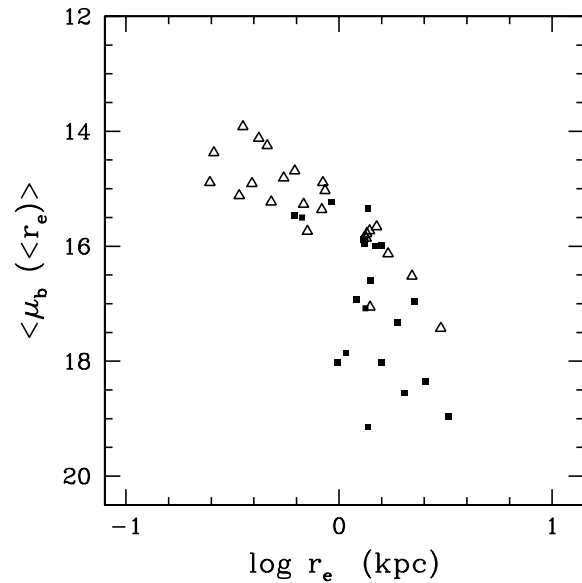


Figure 9. Dependence of the mean surface brightness within bulge effective radius ($\langle\mu_b(<r_e)\rangle$) on bulge effective radius r_e as a function of environment. Faint field lenticulars are shown as open triangles while faint cluster lenticulars are plotted as filled squares.

inately in low density environments. One of the stronger trends seen in the morphology-density relation at low redshift is the dramatic increase in the number of lenticular galaxies in rich clusters (Dressler et al. 1997), suggesting that the dominant process in defining the morphology-density relation is the transformation of spiral galaxies into lenticular galaxies within rich clusters (Poggianti et al. 1999; Kodama & Smail 2001). These spiral galaxies are continuously supplied by accretion from the surrounding field during the course of the assembly of the cluster. *Hubble Space Tele-*

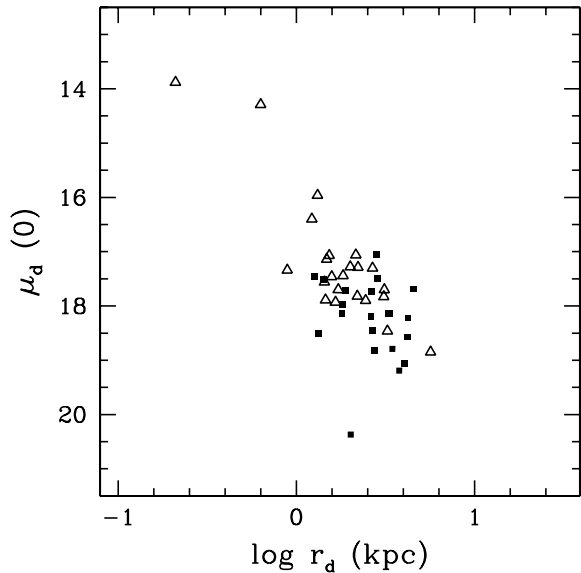


Figure 10. Unconvolved disk central surface brightness $\mu_d(0)$ is plotted against disk scale length r_d as a function of environment. Symbols are as in Figure 9.

scope (*HST*) imaging of 10 clusters at higher redshift ($z \sim 0.3-0.5$) by Dressler et al. 1997 shows similar behaviour. The mechanisms proposed for morphological transformation of spirals to lenticulars include dynamical interactions such as galaxy harassment (Moore et al. 1996, 1998, 1999) and gas dynamical processes e.g. ram pressure stripping (Abadi et al. 1999). Simulations have shown that galaxy harassment is a very efficient mechanism for transforming early-type disk galaxies to lenticulars (Moore 1999) with consequent reduction in disk sizes. Ram pressure stripping truncates the star formation by removing the cold neutral gas reservoir causing the disk component of a spiral galaxy to fade within the cluster environment.

To address these possibilities observationally, it is necessary to investigate how scaling relations defined by various galaxy properties vary between field and cluster environments. In this section, we examine a few correlations as a function of environment. Unfortunately, we are unable to include bright lenticulars in this comparison because only 3 cluster galaxies out of the 38 in our sample, are bright. For faint galaxies, the number of galaxies in the field and in clusters are almost equal, making a comparison possible.

The Kormendy relation for faint lenticulars plotted in Figure 2 shows two distinct groups, unlike bright lenticulars. To investigate the origin of this dichotomy in the faint lenticulars, we plot the Kormendy relation for faint lenticulars, differentiating them by environment, in Figure 9. We indicate field lenticulars with open triangles and cluster lenticulars with filled squares. The field lenticulars seem to follow the Kormendy relation reasonably well while the cluster lenticulars show a clear downward scatter with respect to the relation. On average, this requires a $1.5 \text{ mag arcsec}^{-2}$ fading of the mean surface brightness within r_e of faint cluster lenticulars, with respect to the Kormendy relation. Boselli & Gavazzi (2006) have suggested that low-luminosity lenticulars in clusters might be the result of ram pressure stripping of late-type galaxies, which causes fading and thus lowers surface brightness.

It is interesting to see if this fading is also seen for the disk component. In Figure 10, we plot the disk central surface bright-

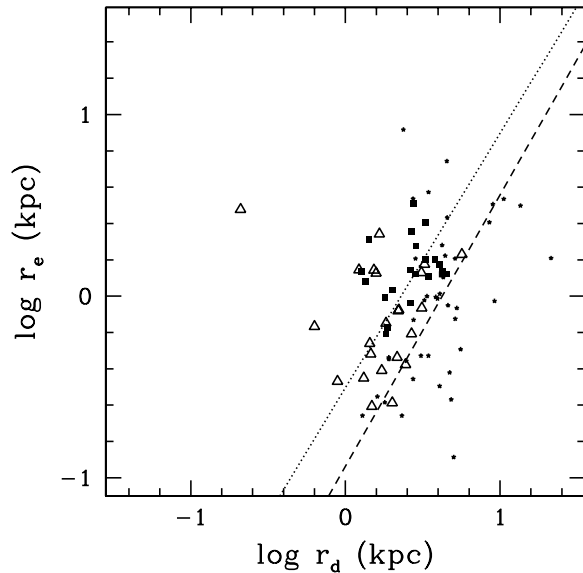


Figure 11. Dependence of the $r_e - r_d$ relation on the environment in K band for the faint lenticulars. Late-type spirals (as asterisks) are overplotted for comparison. Other symbols are as in Figure 9. The dotted line is the best fit to the faint lenticulars (field as well as cluster) excluding the one obvious outlier while the dashed line is the best fit to late-type spirals. Note that these two lines have similar slopes but a different intercept.

ness against the disk scale length. As above, we indicate faint field and cluster lenticulars with different symbols. The faint field lenticulars exhibit a clear anti-correlation, whereas the cluster lenticulars occupy a limited region of the plot and show a downward scatter (indicating fading of the disk), very similar to the scatter seen in Figure 9. Our results obtained using only photometric data are consistent with the spectroscopic results of Barr et al. (2007), which support the theory that lenticular galaxies are formed when gas in normal spirals is removed (from both bulge and disk), possibly when well formed spirals fall into the cluster. It must be noted that the sample of Barr et al. (2007) is a subset of the BAM06 sample, which is included in our analysis.

If lenticulars in clusters are indeed transformed spirals, it is likely that they preserve other signatures of their earlier existence. For instance, if they contained pseudobulges that formed through secular evolution, their bulge and disk sizes should be correlated (Courteau et al. 1996). In Figure 11, we plot the bulge effective radius against the disk scale length for faint lenticulars (a similar plot for bright lenticulars may be found in Barway et al. (2007)). Faint field and cluster lenticulars seems to both follow the same correlation, but inhabit different regions of the plot. We also overplot data for a sample of late-type disk galaxies from Möllenhoff & Heidt (2001). The correlation for faint lenticulars and late type spirals has similar slopes ($\sim 1.40 \pm 0.14$) but different intercept which is expected as late-type spirals have larger disk scale length compared to faint lenticulars. This is a natural expectation if late-type spirals are transforming into faint lenticulars due to interaction with the cluster medium as well as with other galaxies in the cluster.

5 SUMMARY

The main results of this paper are: Several correlations such as the Kormendy relation, photometric plane etc. support the hypothesis

that bright and faint lenticulars (in cluster or field environments) are fundamentally different, with different formation histories. Bright lenticulars resemble ellipticals and bulges of early-type spirals suggesting that they may have formed like them - at early epochs via major mergers or rapid collapse. Faint lenticulars, on the other hand, have properties consistent with them having formed via internal secular evolution processes (in the field) or via environment influenced secular evolution processes such as minor mergers, ram pressure stripping and galaxy harassment (in clusters). Although the dominant differentiating parameter between the two lenticular classes is luminosity, the environment also seems to play a role in determining the details of lenticular formation. In particular, the cluster environment seems to induce a fading of the bulge and the disk and possible transformation in morphology from spiral to lenticular, at least for the faint lenticular population.

If the formation scenario of bright and faint lenticulars is indeed completely different, it should also manifest as differences in star formation history. These differences can be probed using a combination of population synthesis models and multiband bulge disk decompositions. We intend to carry out such an analysis in a future project.

ACKNOWLEDGEMENTS

We thank the anonymous referee for insightful comments that improved the content and presentation of this paper. We thank A. G. Bedregal and A. Aragón-Salamanca for providing us their bulge-disk decomposition results in electronic form. We thank Somak Raychaudhury, Swara Ravindranath, S. K. Pandey and C. D. Ravikumar for helpful discussions. This research has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation.

REFERENCES

- Abadi M. G., Moore B., Bower R. G., 1999, MNRAS, 308, 947
 Barr J. M., Bedregal A. G., Aragón-Salamanca A. et al. 2007, A&A, 470, 173
 Barway S., Mayya Y. D., Kembhavi A. K., & Pandey S. K., 2005, AJ, 129, 630
 Barway S., Kembhavi A., Wadadekar Y., Ravikumar C. D., Mayya Y. D., 2007, ApJ, 661, L37
 Bedregal A. G., Aragón-Salamanca A., & Merrifield M. R., 2006, MNRAS, 373, 1125 (BAM06)
 Bekki K., 1998, ApJ, 502, L133
 Boselli A., Gavazzi G., 2006, PASP, 118, 517
 Bothun, G. D., Gregg M. D., 1990, ApJ, 350, 73
 Buta, R., Laurikainen, E., Salo, H. et al. 2006, AJ, 132, 1859
 Courteau S., de Jong R. S., Broeils, A. H., 1996, ApJ, 457, L73
 Cruz-Gonzalez I., Carrasco L., Ruiz E., Salas L. et al. 1994, RMxAA, 29, 197
 Djorgovski S., Davis M., 1987, ApJ, 313, 59
 Dressler A., 1980, ApJ, 236, 351
 Dressler A., 1987, ApJ, 313, 42
 Dressler A., Oemler A. Jr. et al. 1997, ApJ, 490, 577
 Gadotti, D. A., Athanassoula, E., Carrasco, L., et al. 2007, MNRAS, 381, 943
 Hubble E. P., 1936, The Realm of the Nebulae, Yale University Press
 Jarrett T. H., Chester T. et al. 2003, AJ, 125, 525
 Khosroshahi H. G., Wadadekar Y., Kembhavi A., & Mobasher B., 2000a, ApJ, 531, L103
 Khosroshahi H. G., Wadadekar Y., & Kembhavi A., 2000b, ApJ, 533, 162
 Kodama T., Smail L., 2001, MNRAS, 326, 637
 Kormendy J. 1977, ApJ, 218, 333
 Kormendy J., & Kennicutt R. C. Jr., 2004, *Ann. Rev. Astron. Astrophys.*, 42, 603
 Laurikainen, E., Salo, H., Buta, R. 2005, MNRAS, 362, 1319
 Laurikainen, E., Salo, H., Buta, R. et al. 2006, AJ, 132, 2634
 Lima Neto G. B., Gerbal D., & Márquez I., 1999, MNRAS, 309, 481
 Metropolis N., Rosenbluth, N., Rosenbluth, A., Teller, A., & Teller, E. 1953, *Journal of Chemical Physics*, 21, 1087
 Mobasher B., Guzman R., Aragón-Salamanca A., Zepf S. 1999, MNRAS, 304, 225
 Möllenhoff C., Heidt J., 2001, A&A, 368, 16
 Moore B., Katz N., Lake G., Dressler A., & Oemler A., 1996, Nature, 379, 613
 Moore B., Lake G., & Katz N., 1998, ApJ, 495, 139
 Moore B., Lake G., Quinn T., & Stadel J., 1999, MNRAS, 304, 465
 Peletier R. F., Balcells M., 1996, AJ, 111, 2238
 Peletier R. F., & Balcells M., 1997, *New Astronomy*, 1, 349
 Peng C. Y., Ho L. C., Impey C. D., Rix H., 2002, AJ, 124, 266
 Poggianti B. M. et al. 1999, ApJ, 518, 576
 Simard L. et al. 2002, ApJS, 142, 1
 Sérsic J. L., 1968, Atlas de Galaxias Australes (Cordoba: Obs. Astron.)
 de Souza R. E., Gadotti D. A., dos Anjos S., 2004, ApJS, 153, 411
 van den Bergh S., 1994, AJ, 107, 153
 Wadadekar Y., Robbason B., & Kembhavi A., 1999, AJ, 117, 1219