Lenticular Galaxy Formation - Possible Luminosity Dependence

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ABSTRACT

We investigate the correlation between the bulge effective radius (r_{e}) and disk scale length (r_{d}), in the near-infrared K band for lenticular galaxies in the field and in clusters. We find markedly different relations between the two parameters as a function of luminosity. Lenticulars with total absolute magnitude fainter than $M_T = -24.5$ show a positive correlation, in line with predictions of secular formation processes for the pseudo bulges of late-type disk galaxies. But brighter lenticulars with $M_T < -24.5$ show an anti-correlation, indicating that they formed through a different mechanism. The available data are insufficient to reliably determine the effect of galaxy environment on this correlation.

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

1. Introduction

Lenticular (S0) galaxies form a morphological transition class between ellipticals and early-type spirals in the Hubble (1936) classification system. They have disks with luminosity ranging from ten to hundred percent of the bulge. The use of lenticulars as a transition class may be justified by the fact that in many of their observable properties such as B/T ratio, colors and spectral properties, neutral and molecular gas fraction, star formation rates, average luminosity and M/L ratio, the more luminous lenticulars (which dominated the magnitude limited samples during Hubble's time) straddle the gap between ellipticals

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and spirals. When comparing properties, it is found that the bulges of lenticulars are very similar to elliptical galaxies, while their disks have similarities to the disks of early type spiral galaxies, except that they lack conspicuous spiral arms (see the review by Fritze – v. Alvensleben 2004). It has recently been suggested by Bedregal, Aragón-Salamanca, & Merrifield (2006) and Aragón-Salamanca, Bedregal, & Merrifield (2006) that a significant fraction of lenticulars are faded spirals. Our understanding of the formation and evolution of lenticular galaxies, in terms of the individual physical processes involved, is still unclear, inspite of extensive efforts both by observational and theoretical means (van den Bergh 1976, 1990; Bothun 1982, Bekki et al. 2002).

Over the last decade, it has become increasingly clear that the bulge component of galaxies comes in two varieties, distinct in their properties and parameter correlations (Ravikumar et al. 2006 and references therein). Available evidence indicates that the *classical bulges* found in ellipticals and early type disk galaxies formed at an early cosmic epoch from the rapid transformation events caused by hierarchical clustering and merging of comparable mass galaxies. Such bulges typically are old and often show higher anisotropic velocity dispersion in their stellar kinematics. Their light profile is usually well represented by the Sérsic (1968) law with larger n values ($n \sim 4$), and they often show boxy isophotes. Classical bulges show correlations in their global photometric and dynamical properties, like the Fundamental plane (Djorgovski & Davis 1987, Dressler et al. 1987) and the Photometric plane (Khosroshahi et al. 2000a, Ravikumar et al. 2006), reflecting their virialized nature or maximized entropy (Lima-Neto, Gerbal, & Márquez 1999).

The younger, bluer bulges found in late-type disk galaxies, which usually have exponential light profiles and disky isophotes, are largely rotationally supported. These weaker *pseudo bulges* (see detailed review by Kormendy & Kennicutt 2004) likely formed in a dissipational process due to vertical dynamical instabilities of the disks (Combes et al. 1990; Hasan, Pfenniger, & Norman 1993) and subsequently grew through secular evolution by gas infall into the central regions, possibly channeled through a bar. The secular evolution process may be episodic and may still be growing pseudo-bulges in late type disk galaxies today (Kormendy & Kennicutt 2004).

Given that lenticulars are intermediate between ellipticals and early-type spirals in many of their properties, one might expect that the bulge component of lenticulars is of the classical type. N-body simulations support the view that the spheroidal component of massive and more luminous lenticulars is formed by the major merger of disk systems in a prograde or retrograde encounter (Bekki 1995), in a process similar to the merger driven formation processes for ellipticals and bulges of early-type spiral galaxies. Such mergers, after a few Gyr, show elliptical galaxy like colors and spectra in evolutionary synthesis models (Fritze

– v. Alvensleben & Gerhard 1994a,b). However, such a merger scenario is only viable in the field or within infalling groups where galaxy encounter velocities are sufficiently low for efficient merging. Minor mergers (or accretion events), on the other hand, are a viable route to the formation of low luminosity lenticulars as demonstrated by N-body simulations (Barnes 1996; Bekki 1998). In such encounters, stripping of gas from the halo and disk of spiral galaxies (Bekki et al. 2002) is accompanied by a change in morphology. For such galaxies, the standard arrangement of lenticulars on the Hubble sequence may need to be revised. A suitable classification for low luminosity lenticulars may be the one proposed by van den Bergh (1979, 1998) wherein the lenticular galaxies form a sequence parallel to spirals with S0a, S0b, and S0c being the gas-stripped lenticular analogues of Sa, Sb, and Sc galaxies respectively. If indeed a fraction of lenticulars formed from spiral galaxies, the B/T flux ratio should be comparable between these analogous classes. Recently, Laurikainen et al. (2006) have found lenticular galaxies where the B/T flux ratio is as small as in typical Sc-type spirals.

Which of the models of bulge formation operates as a function of galaxy luminosity and environment may be tested by confronting the predictions of bulge formation models and N-body simulations with observations. Bulge formation models make some testable predictions mostly in the form of correlations expected in the global photometric properties of bulges and disks. For example, secular bulge formation models predict that the bulge and disk scale lengths be correlated (Martinet 1995; Combes 2000; see Carollo, Ferguson, & Wyse 1999 for comprehensive review articles). On the other hand, classical bulges exhibit correlations such as the fundamental plane and the photometric plane mentioned above. Such predictions can be tested quantitatively by measuring these parameters using one of the several available bulge-disk decomposition codes (e. g. Wadadekar, Robbason, & Kembhavi 1999; Peng et al. 2002).

In this Letter, we examine correlations amongst the photometric parameters of bulge and disk components of lenticular galaxies, in the near-infrared K band, as a probe of likely formation mechanisms. Our goal is to investigate the relative importance of mergers and secular evolution in the formation of the bulge component, as a function of luminosity and environment. Throughout this Letter, we use $H_0 = 70$ km s^{-1} Mpc^{-1}.

2. The Data and Decomposition Technique

Our sample consists of a set of 35 bright field lenticular galaxies from Barway et al. (2005), observed in the K band using the 2.1m telescope at Observatorio Astronomico Nacional, San Pedro Martir, Mexico. The original sample contained 40 lenticulars galaxies, selected from the Uppsala General Catalogue (UGC), with apparent magnitude $B < 14$, angular diameter $D_{25} < 3$ arcmin and declination $5^\circ < \delta < 64^\circ$. The sample, while not complete, is representative of bright field lenticulars. Further details on sample selection, observation and data reduction procedures can be found in Barway et al. (2005).

We extracted the bulge and disk parameters for our sample galaxies using a two- dimensional bulge-disk decomposition technique, which employs a χ^2 minimization algorithm as described in Wadadekar et al. (1999). We decomposed all the galaxies in our sample into a bulge component with surface brightness distribution given by the $\mathrm{r}^{1/n}$ law (Sérsic 1968) with

$$I_{\mathrm{b}}(r) = I_{\mathrm{b}}(0) e^{-2.303 b_n (r/r_{\mathrm{e}})^{1/n}}, \tag{1}$$

where n is the Sérsic index, $I_{\mathrm{b}}(0)$ is the bulge central intensity and the constant b_n is chosen such that r_{e} is the half light radius for every value of n; b_n is the root of the equation

$$P(2n, 2.303 b_n) = 0.5, \tag{2}$$

where $P(a,x)$ is the incomplete gamma function (see e. g. Press et al. 1992).

The disk profile is well approximated by an exponential $I_{\mathrm{d}}(r) = I_{\mathrm{d}}(0) e^{-(r/r_{\mathrm{d}})}$, where r_{d} is the disk scale length and $I_{\mathrm{d}}(0)$ is the disk central intensity. Apart from the five parameters mentioned above, the fit also involves the bulge and disk ellipticities and the sky background. Intensity models convolved with the appropriate point-spread function (PSF) determined from stars present in the galaxy image are fitted to the observed images so as to minimize χ^2. Of the 40 lenticulars in Barway et al. (2005), we obtained satisfactory fits for the 35 galaxies which we have included in the present analysis.

We augment our sample with data from Bedregal, Aragón-Salamanca, & Merrifield (2006; hereafter BAM06) on 49 lenticular galaxies. These are relatively faint objects with sufficient rotational support for the disks. BAM06 used the Two Micron All Sky Survey (2MASS; Jarrett et al. 2003) data in the K_s band to obtain bulge and disk parameters using the 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.

The BAM06 galaxies complement our sample in two ways: They extend to fainter luminosities and provide lenticulars in different environments. The sample contains galaxies from the Coma (14), Virgo (8), and Fornax (6) clusters along with 21 field lenticulars. 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.

3. Bulge-Disk Correlations

Correlations between the bulge and disk parameters can provide important information on their interplay and evolution. Courteau, de Jong, & Broeils (1996) reported a correlation between bulge half-light radius (effective radius) $r_{\rm e}$ and disk scale length $r_{\rm d}$ for late-type spiral galaxies (see also de Jong 1996), which was later confirmed by Khosroshahi, Wadadekar, & Kembhavi (2000b). Bulge and disk size correlations are well understood in models in which the disk forms first and the bulge emerges from the disk, via angular momentum redistribution processes (Combes et al. 1990; Saio & Yoshi 1990; Struck-Marcell 1991). On the contrary, models which predict disk formation from an existing central bulge, do not support the idea of a strong bulge-disk size correlation.

In Figure 2(a) we plot bulge effective radius ($r_{\rm e}$) against the disk scale length ($r_{\rm d}$) for the BAM06 sample, with open circles representing field lenticulars and filled triangles representing lenticulars in clusters. The 21 field lenticulars show a strong positive correlation, with linear correlation coefficient 0.63 at a significance level better than 99.99% [5]. This is similar to the correlations reported for early-type spiral galaxies by Khosroshahi et al. (2000b) and for late-type spiral galaxies by Courteau et al. (1996). The 28 cluster lenticulars have a correlation coefficient of 0.22 between $r_{\rm e}$ and $r_{\rm d}$, which is significant at the 74.00% level. While this level is too low for the correlation to be accepted as established, we can say that the trend is consistent with the significant positive correlation found for the field lenticulars. Moreover, amongst the cluster lenticulars, there are three clear outliers. Inspection of their 2MASS K-band images shows that one of these (ESO 358-G59) has poor signal-to-noise ratio, while the other two (NGC 4638 and NGC 4787) are obviously disk dominated systems, which are likely to have disk scale lengths large than those reported by BAM06. We will omit these three outliers from further discussion, while noting that our conclusions are not changed by this omission. After the omission, the $r_{\rm e} - r_{\rm d}$ correlation coefficient for the cluster lenticulars increases to 0.61 with significance greater than 99.99%.

We have shown in Figure 2(b) the variation of $r_{\rm e}$ with $r_{\rm d}$ for our sample of 35 lenticulars. A majority (27/35) of field lenticulars from the sample show a clear anti-correlation with correlation coefficient -0.57 at a significance level of 99.82%. All these lenticulars are found to have bulge luminosity exceeding the disk luminosity, with mean bulge-to-total luminosity ratio $\langle B/T \rangle = 0.63$. The corresponding value for the BAM06 lenticulars is $\langle B/T \rangle = 0.55$. A separate group of lenticulars which do not follow the anti-correlation is seen in the lower part

[5] We have also used Spearman's rank correlation coefficient to examine the trends reported in the the paper. We find in every case the significance of Spearman's coefficient is higher than the significance of the linear correlation coefficient we quote in the text.

of the diagram. These are found to be disk dominated systems with low mean bulge-to-total luminosity ratio $\langle B/T \rangle = 0.19$. The anti-correlation applies only to the bulge dominated systems.

The difference between the BAM06 sample and our sample in the sign of the $r_{\rm e} - r_{\rm d}$ correlation is unlikely to be due to environmental effects, since within the BAM06 sample, field lenticulars as well as those in clusters show the same positive correlation. However, as galaxies in the BAM06 sample are systematically less luminous than those in our sample, it could be that the fainter lenticular galaxies, irrespective of their environment, show a positive $r_{\rm e} - r_{\rm d}$ correlation, while the more luminous lenticulars exhibit a negative correlation. To test this hypothesis, we combine both samples and then divide them into faint and bright groups, using $M_T = -24.5$ as boundary. The 43 faint lenticulars ($M_T > -24.5$), with the outlier indicated in Figure 3 excluded, show positive correlation between the bulge effective radius and disk scale length with correlation coefficient 0.48 at a significance level better of 99.89%. On the other hand, the 32 bright lenticulars ($M_T < -24.5$), again excluding five obvious outliers, show a strong anti-correlation with correlation coefficient −0.64 at a significance level of 99.99% (see Figure 3). We note here that the boundary at $M_T = -24.5$ is merely indicative, and the result does not critically depend on the choice of the dividing luminosity. Changing this value by half a magnitude on either side leads to correlations significant at least at the 95% level. We may therefore say that the sense of the correlation is driven by the luminosity of the galaxies, pointing to a possible fundamental difference in the way in which faint and bright lenticulars are formed. The positive correlation seen in low luminosity galaxies lends support to the hypothesis that such galaxies formed by the stripping of gas from the halo and disk of late type spiral galaxies, which formed their bulges through secular evolution. More luminous lenticulars likely formed their bulges differently, possibly through a rapid collapse mechanism. We may mention here that dividing the entire sample of lenticulars into bulge dominated and disk dominated systems, using a boundary value of $B/T = 0.5$ or the median value 0.53 for the whole sample, does not produce two well correlated subsamples. This is consistent with the fact that a plot of B/T against total luminosity shows no obvious correlation. The luminosity therefore seems to be the main driver for the difference in the $r_{\rm e} - r_{\rm d}$ correlation seen in the population of lenticulars.

It has been known for some time that the *average* Sérsic index n systematically decreases from early to late type galaxies (Andredakis, Peletier, & Balcells 1995; Khosroshahi et al. 2000b). This decrease is only observed in a statistical sense; for any specific Hubble type there is considerable range in the measured values of n. If low luminosity lenticulars are indeed evolved late-type disk galaxies, then they should have lower values of the Sérsic index compared to brighter lenticulars. We do find that for our combined sample, distribution of the Sérsic index for the faint lenticulars has a peak at $n \sim 3.25$ while that for bright lenticulars has a peak at $n \sim 3.75$.

4. Summary

We find that lenticular galaxies show markedly different correlations between their bulge effective radius (r_e) and disk scale length (r_d) as a function of their total luminosity. For faint lenticular galaxies ($M_T > -24.5$), r_e and r_d are positively correlated, in line with predictions of secular formation processes that likely formed the pseudo bulges of late-type disk galaxies. Such a formation scenario is also consistent with the predictions of numerical simulations of lenticular galaxy formation (Quilis, Moore, & Bower 2000). Bright lenticular galaxies with $M_T < -24.5$, on the other hand, do not exhibit this correlation, indicating a different formation mechanism. These trends seem to hold irrespective of galaxy environment, although more luminous lenticulars are largely missing from our cluster sample. The relative fraction of lenticular galaxies is, of course, very different in clusters and in the field.

The correlations reported in this letter, need to be investigated with larger near-IR samples of lenticular galaxies, to unravel possible multiparametric correlations which will take into account the dependence on luminosity and environment and provide a detailed comparison with other galaxy types. Such a study will be enabled in the near future by new data such as the Large Area Survey component of UKIDSS.

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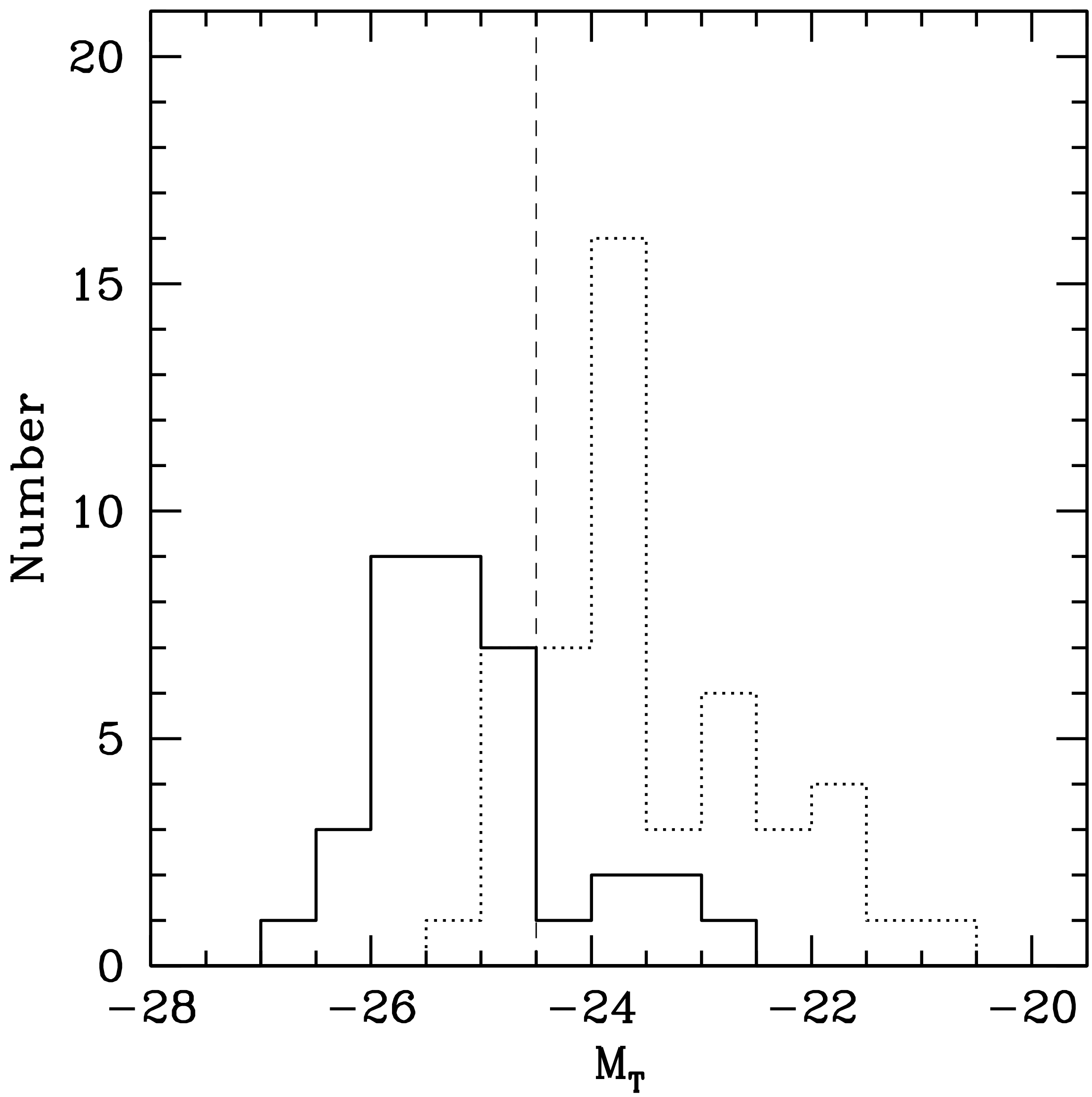

Fig. 1.— Distribution of total absolute magnitude (M_T) in K band for our sample (solid line) and for BAM06 lenticulars (dotted line). Vertical dashed line corresponds to total absolute magnitude $M_T = -24.5$, which we use to separate low and high luminosity lenticulars.

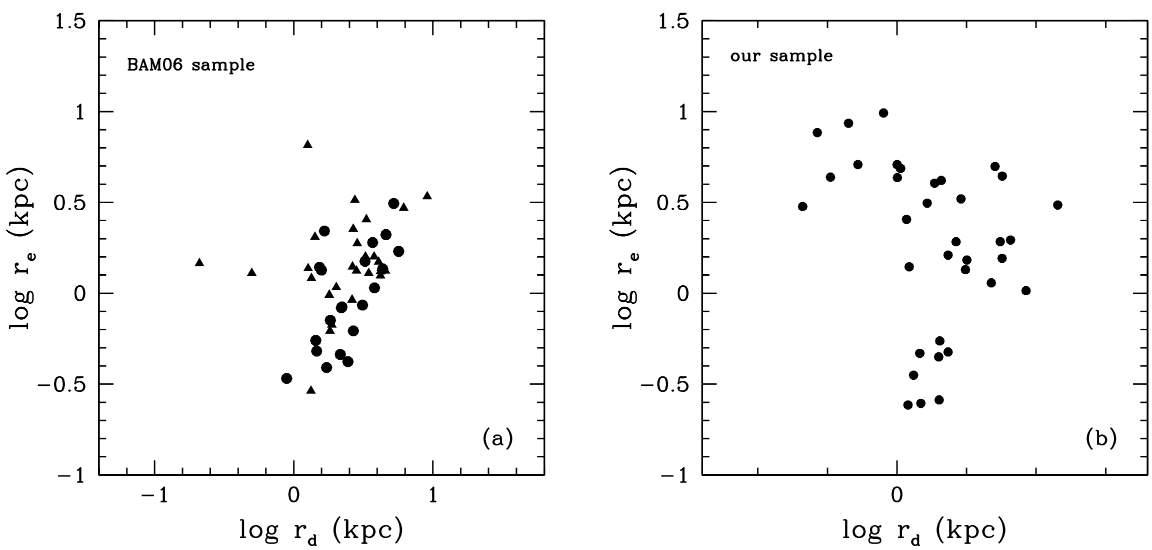

Fig. 2.— The bulge effective radius (r_e) plotted as a function of disk scale length (r_d) for lenticular galaxies (a) from BAM06 sample and (b) our sample. Lenticulars in the field and clusters are denoted by circles and triangles, respectively.

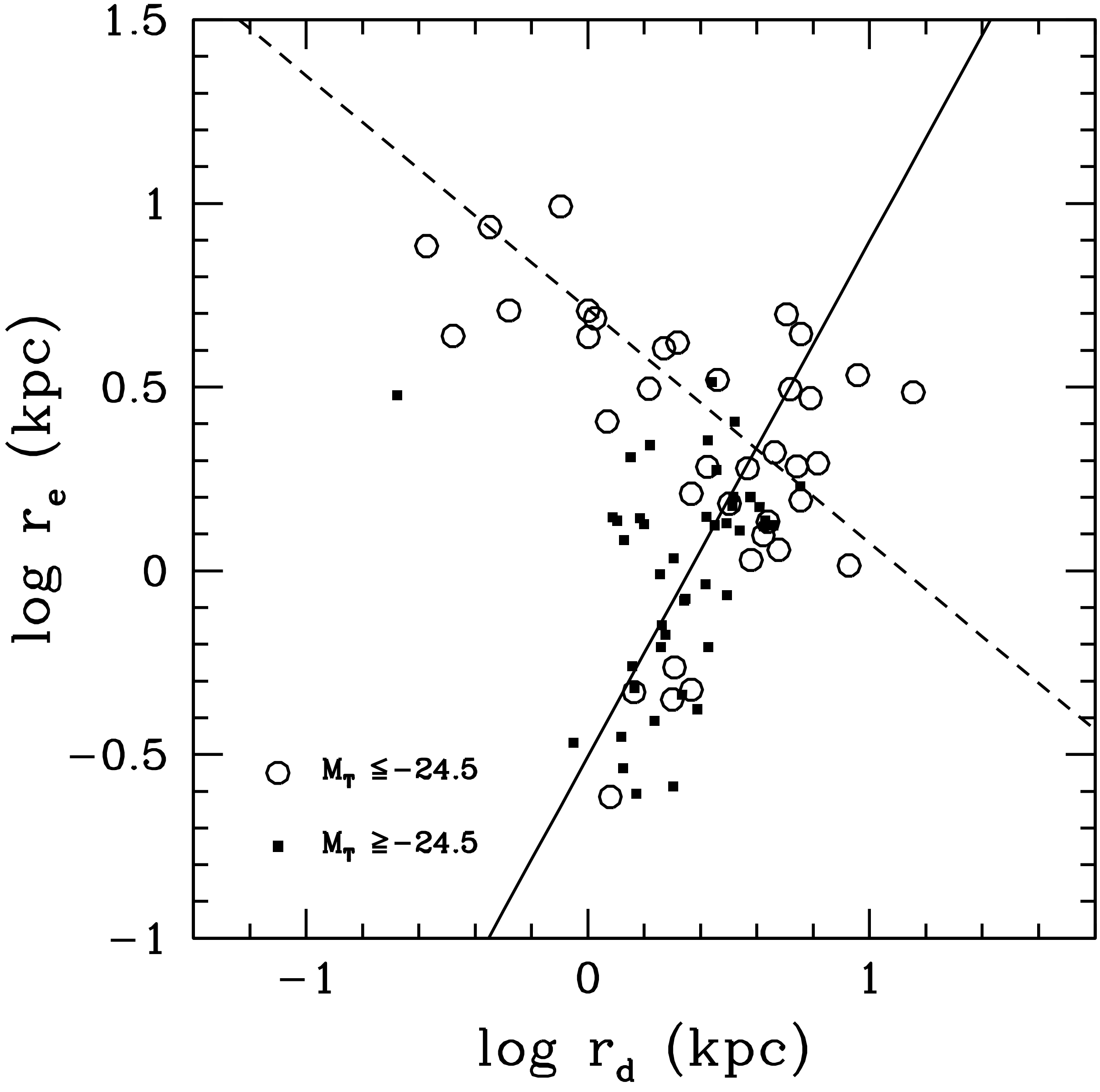

Fig. 3.— Dependence of $r_{\rm e}$-$r_{\rm d}$ relation on the total absolute magnitude in K band for the combined sample (ours+BAM06) of lenticulars. Dashed line is the best-fit to the luminous lenticulars (open circles) excluding five outliers, with correlation coefficient −0.64 at 99.99% significance level. Solid line is the best-fit to the less luminous lenticulars (filled squares, excluding one outlier) with correlation coefficient 0.48 at 99.89% significance level.