# A MORPHOLOGICAL-TYPE DEPENDENCE IN THE $\mu_0$–$\log h$ PLANE OF SPIRAL GALAXY DISKS

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## ABSTRACT

We present observational evidence for a galaxy 'Type' dependence to the location of a spiral galaxy's disk parameters in the $\mu_0$–$\log h$ plane. With a sample of ∼40 Low Surface Brightness galaxies (both bulge- and disk-dominated) and ∼80 High Surface Brightness galaxies, the early-type disk galaxies (≤Sc) tend to define a bright envelope in the $\mu_0$–$\log h$ plane, while the late-type (≥Scd) spiral galaxies have, in general, smaller and fainter disks. Below the defining surface brightness threshold for a Low Surface Brightness galaxy (i.e. more than 1 mag fainter than the 21.65 B-mag arcsec$^{-2}$ Freeman value), the early-type spiral galaxies have scale-lengths greater than 8-9 kpc, while the late-type spiral galaxies have smaller scale-lengths. All galaxies have been modelled with a seeing-convolved Sérsic $r^{1/n}$ bulge and exponential disk model. We show that the trend of decreasing bulge shape parameter ($n$) with increasing Hubble type and decreasing bulge-to-disk luminosity ratio, which has been observed amongst the High Surface Brightness galaxies, extends to the Low Surface Brightness galaxies, revealing a continuous range of structural parameters.

*Subject headings:* galaxies: fundamental parameters (scale-lengths, surface brightness, bulge-to-disk ratio), galaxies: kinematics and dynamics, galaxies: photometry, galaxies: spiral, galaxies: structure

## 1. Introduction

During the closing decade of the 1900s considerable progress was made in the observation and parameterization of intrinsically faint spiral galaxies (van der Hulst et al. (1993); de Blok et al 1995; Sprayberry et al. 1995; Bothun, Impey, & McGaugh 1997; Beijersbergen, de Blok, & van der Hulst 1999). Galaxies with a central disk surface brightness more than one magnitude fainter than the canonical Freeman (1970) value of 21.65 B-mag arcsec$^{-2}$ were defined to be Low Surface Brightness (LSB) galaxies. Spiral galaxies with a brighter central disk surface brightness have subsequently been labelled High Surface Brightness (HSB) galaxies, and it is these galaxies which typify the Hubble sequence. Although, in reality, this threshold is somewhat arbitrary as observations of many spiral galaxies reveals a smooth continuation in central disk surface brightness values across this boundary. The existence of LSB galaxies – including knowledge of the extreme LSB galaxy 'Malin 1' (Bothun et al. 1987, Impey & Bothun 1989) – had of course been known many years earlier (Longmore et al. 1982; Davies et al. 1988), and had been previously predicted, on the grounds of

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visibility arguments Disney (1976).

In this Letter we combine the data from two LSB galaxy samples with a representative sample of HSB galaxies containing all spiral morphological types. The objective is to explore the tentative suggestion of Graham (2001a) that a morphological type dependence exists in the central disk surface brightness – disk scale-length ($\mu_0$–$\log h$) diagram. Re-analyzing the light-profiles from the diameter-limited sample of 86 spiral galaxies from de Jong & van der Kruit (1994) and de Jong (1996), Graham (2001a) noted that the low surface brightness (high $\mu_0$) small disk scale-length corner of the $\mu_0$–$\log h$ diagram was dominated, in fact, only populated, by late-type spiral galaxy disks. To be somewhat more quantitative, the host galaxies of disks with scale-lengths less than 9 kpc and central surface brightnesses fainter than 19.0 K-mag arcsec$^{-2}$ were all late-type spiral galaxies (>Sc). To investigate this further, this same galaxy sample is supplemented here with two of the largest samples of LSB galaxies measured with CCDs. The first is a sample of ~20 'disk-dominated' LSB galaxies from de Blok et al. (1995), and the second is a sample of ~20 'bulge-dominated' LSB spiral galaxies (Beijersbergen et al. 1999).

The selection criteria for the three data samples are reviewed in Section 2, and the derivation of the light-profile model parameters is also discussed there. All of the galaxies have been modelled by us using the same bulge/disk decomposition algorithm. We additionally provide the first quantitative measurement to the prominence, and/or absence, of the bulges in 'disk-dominated' LSB galaxies. The resulting distribution of disks in the $\mu_0$–$\log h$ diagram is presented in Section 3.

## 2. Data

### 2.1. The galaxy sample

The data selection procedure, and method of reduction, are described in detail in the above mentioned papers. We will only comment here on the selection criteria – relevant to concerns about possible biases which might result in an under-estimation of early-type spirals in the low surface brightness (high $\mu_0$) small scale-length corner of the $\mu_0$–$\log h$ diagram.

de Jong & van der Kruit (1994) selected 'undisturbed' spiral galaxies from the UGC catalog (Nilson 1973) if they had a red minor-axis to major-axis ratio greater than 0.625 (i.e. inclinations less than ~50°), a red major-axis $\geq 2.0'$, and an absolute galactic latitude greater than 25°. Telescope time and pointing restrictions resulted in a final sample of 83 spiral galaxies with types ranging from Sa to Sm (plus one S0 and two Irregular galaxies). None of their selection criteria are expected to create a morphological-type bias.

Beijersbergen et al. (1999) selected spiral galaxies from the ESO-LV catalog (Lauberts & Valentijn 1989) to have types ranging from Sa-Sm, inclinations less than 50°, and absolute galactic latitudes greater than 15°. They additionally required the diameters of the 26 B-mag arcsec$^{-2}$ isophote to be greater than $1'$and smaller than $3'$(chip size limitation), and the surface brightness of the disk at the half-light radii to be fainter than 23.8 B-mag arcsec$^{-2}$. From the resulting list of some 600 galaxies, a random sample which had central light concentrations was selected. This prescription certainly should not have biased against the selection of early-type spiral galaxies, but on the contrary selected them if they do indeed exist.

de Blok et al. (1995) selected galaxies from the late-type sample of LSB UGC galaxies from van der Hulst et al. (1993) and the lists by Schombert & Bothun (1988) and Schombert et al (1992). Of the 17 galaxies from the de Blok sample for which we have B-band data, 2 originate from the van der Hulst UGC sample. The others are from the Schombert LSB galaxy lists which were constructed from a visual inspection of sky survey plates, and contain no *a priori* bias against early-type spiral galaxies. de Blok et al. randomly selected a sub-set of galaxies with inclinations less than 60°, central surface brightnesses fainter than 23 B-mag arcsec$^{-2}$, and having single-dish $H_I$ observations available. This last criteria is the only possible bias we can identify (given that some early-type spiral galaxies may be gas-poor) ; however, it is expected to be a small effect for the following reason. The morphological make-up of the LSB galaxy catalogs of Schombert et al. (consisting of objects not in the UGC) turned out to be dominated (85%) by late-type galaxies (another 10% are dwarf ellipticals and some 5% unclassifiable). The reason for this composition is that the prominence of the bulge in early-type spiral galaxies had resulted in their prior detection in the first-generation Palomar sky-survey plates used by Nilson. The second-generation sky-survey plates went about a magnitude deeper, and predominantly resulted in the detection of fainter late-type galaxies. Thus, even if the $H_I$ requirement excluded *all* early-type galaxies in the LSB catalogs, this would only be a 5-10% bias, which would equate to the exclusion of 1 or 2 early-type galaxies from our sample.

To summarize, the total galaxy sample is likely to be biased in favor of the inclusion of early-type LSB galaxies due to the selection criteria used by Beijersbergen et al. (1999).

### 2.2. The light-profile model parameters

The galaxy light-profiles from the three galaxy samples are already published in the respective papers, and we refer the interested reader to these. For the sake of the present analysis, we have applied the same algorithm to every light-profile, simultaneously fitting a seeing-convolved Sérsic (1968) $r^{1/n}$ bulge and a seeing-convolved exponential disk (see Graham 2001b for details). This is an improvement over previous comparative work between the HSB and LSB galaxies because it not only avoids biases between different authors fitting techniques, but provides a more reliable approach to separating the bulge light from that of the disk. Additionally, this is the first time a bulge model has been fitted to the 'disk-dominated' sample of LSB galaxies. The structural parameters obtained from this decomposition are: the central disk surface brightness ($\mu_0$), the disk scale-length ($h$), the effective radius of the bulge ($r_e$), and the surface brightness of the bulge at this radius ($\mu_e$), and lastly, the shape parameter $n$ from the $r^{1/n}$ bulge model.

After correcting the heliocentric velocity measurements for Virgo-infall using the 220 model of Kraan-Korteweg (1986), the scale-lengths were converted from arcseconds to kpc using a Hubble constant $H_0$=75 km s$^{-1}$ Mpc$^{-1}$. Redshifts for ESO-LV 1590200, ESO-LV 0350110, and ESO-LV 0050050 were obtained from the Parkes telescope HIPASS database (Barnes et al. 2000). Redshifts for the other galaxies came from the respective papers. The surface brightnesses were adjusted for a) $(1+z)^4$ redshift dimming, b) $K$-corrections (using the tables of Poggianti 1997), c) Galactic extinction (Schlegel, Finkbeiner, & Davis 1998; data obtained from NED), and d) inclination corrected. We used the inclination correction $2.5C\log(a/b)$, where $a/b$ is the axis-ratio of the outer disk – assumed to be due to inclination. The value of $C$ was taken to be 0.2 for the $B$-band and 0.5 for the $R$-band (Tully & Verheijen 1997). It is noted that while this correction is necessary for the HSB galaxies, it's relevance to the LSB galaxies is not as clearly established. Both the HSB and the LSB galaxy samples have inclinations less than 60°, and so the maximum correction is 0.15 mag arcsec$^{-2}$ ($B$-band) and $\sim$0.4 mag arcsec$^{-2}$ ($R$-band). The average correction for the LSB galaxies turned out to be only 0.06 ($B$-band) and 0.15 ($R$-band) mag arcsec$^{-2}$, and cannot be a significant bias or explanation for the distribution of points in the $\mu_0$–$\log h$ diagram (Section 3).

We report that only a couple of the late-type LSB galaxies from de Blok et al. (1995) have bulges with central surface brightness values that are brighter than the disk, and even then, only brighter by a few tenths of magnitude. Most of the late-type LSB galaxies have bulges with central surface brightness values that are fainter than that of the disk; their presence signalled by a central bulge in the light-profile that rises less than $0.75(= 2.5\log(2))$ mag (and often much less) above the extrapolated disk light-profile. Many of the light-profiles actually show no sign at all of a bulge. In all the late-type LSB galaxies in the sample, the light distribution is overwhelmingly dominated by that of the disk; however, for those LSB galaxies with bulges, we can perform a comparison study with the HSB galaxy sample.

## 3. The $\mu_0$–$\log h$ diagram

Shown in Figure 1 are the central disk surface brightnesses plotted against the associated disk scale-lengths. In general, the disks from early-type spiral galaxies tend to reside, or rather, define, the upper envelope of points in the $\mu_0$–$\log h$ diagram. The disks of late-type spiral galaxies tend to reside, in general, below this envelope. One can also get a feel for the distribution of points by cutting the diagram up further. While we do not wish to suggest anything physical with an arbitrary cut at 22.65 B-mag arcsec$^{-2}$, it is however somewhat revealing to do so. One can see that the early-type spiral galaxies with central disk surface brightnesses fainter than this value have large disk scale-lengths (>8-9 kpc) while the LSB late-type spiral galaxies have disk scale-lengths less than this. Yet another way to view the diagram is parallel to lines of constant disk luminosity, which have a slope of 5. One can see that, on average, the brightest early-type spiral galaxies have brighter luminosities than the brightest late-type spirals; a result consistent with the luminosity functions of different spiral galaxy types (Folkes et al. 1999). Furthermore, when one factors in the contribution from the bulge light this trend will be stronger still. The data does however reveal that there is some overlap of galaxy types in the diagram. That is, rather than a strict exclusion of a given population in different parts of the $\mu_0$–$\log h$ diagram. it is more a case of one population dominating over the other. This morphological type separation is actually analogous to the behavior of bulges in the $\mu_e$–$\log r_e$ diagram (Kent 1985; his figure 5b).

Past studies of the $\mu_0$–$\log h$ diagram have either been limited to the upper right of the diagram by the selection-criteria, or have not investigated the morphological-type dependence. Bothun et al. 1997 explored beyond the typical selection-criteria boundaries by including in their Figure 4, in addition to a sample of HSB galaxies, a large sample of LSB galaxies. They revealed a similar distribution of points as seen in Figure 1, but no morphological-type distinction was made (similarly see, Dalcanton, Spergel, & Summers 1998 figure 4; McGaugh 1998 figure 1). In reviewing the literature, however, we have found that combining figure 3 from Tully & Verheijen (1997) (a $\mu_0$–$\log h$ diagram) with their figure 6 (a plot of $\mu_0$ vs. galaxy type) should reveal the same morphological-type dependence as observed here, lending support to this result.

The upper boundary in the $\mu_0$–$\log h$ plane represents a real decline to the space-density of galaxies with big (large $h$) bright (low $\mu_0$) disks – the selection criteria favors their detection. The presence of this boundary has been used in Graham (2001a, see also Graham 2000a,b) to estimate the degree of opacity in inclined early-type spiral galaxy disks; inclined galaxies with transparent disks are shown to reside above this envelope due to the apparent brightening of their disk with inclination. The lower boundary is however artificial – the result of a cut-off imposed by the galaxy selection criteria . The existence of ultra-low LSB, optically invisible galaxies (Disney 1998), is therefore not excluded. The (solid) lines of constant luminosity shown in Figure 1 are lines of constant disk luminosity, and therefore do not include possible contributions from the bulge light to the total galaxy light. One may therefore wonder if the upper envelope may in fact represent a boundary of constant 'galaxy' luminosity – perhaps the bright end to the luminosity function. To address this thought, we show in Figure 2 the bulge-to-disk ($B/D$) luminosity ratio, as a function of disk scale-length for every galaxy in the upper envelope delineated by the dotted lines in Figure 1. No trend of increasing $B/D$ luminosity ratio with decreasing scale-length is evident, and consequently no support is given to the suggestion that the upper boundary is due to a maximum galaxy luminosity.

In Figure 3 we have plotted all the $B/D$ luminosity ratios against the bulge shape parameter $n$ (the index from the best-fitting $r^{1/n}$ bulge profile models). These points have been plotted as a function of galaxy type, and also in a way so as to reveal which galaxy sample they have come from. One can see that for both the HSB and LSB galaxies, the shape of the bulge light-profile is correlated with the nature of the host galaxy in the sense that both the $B/D$ luminosity ratio and the galaxy morphological type are correlated with $n$, This result is firmly established for the bulges of HSB spiral galaxies (Andredakis, Peletier, & Balcells 1995; Graham 2001b; Mollenhoff & Heidt 2001), but has not been previously shown for the bulges of LSB spiral galaxies. It would appear that no obvious structural distinction can be made between the LSB and HSB spiral galaxies in this diagram.

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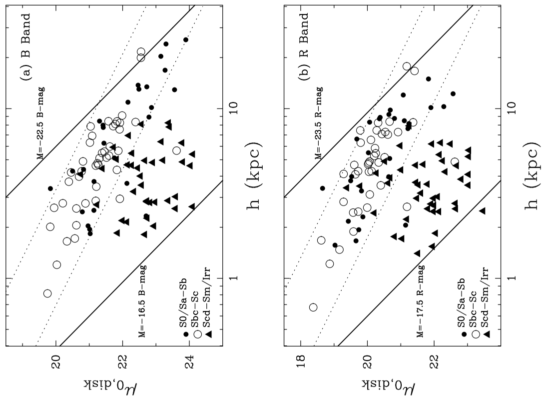


Fig. 1.— (a) The $B$-band central disk surface brightnesses are plotted against the disk scale-lengths ($H_0$=75 km s$^{-1}$ Mpc$^{-1}$). The solid lines are lines of constant disk luminosity (slope equals 5), and the dotted lines have a slope of 2.5. Galaxies of different morphological type are marked with different symbols, according to the legend inset in the diagram. (b) The $R$-band data.

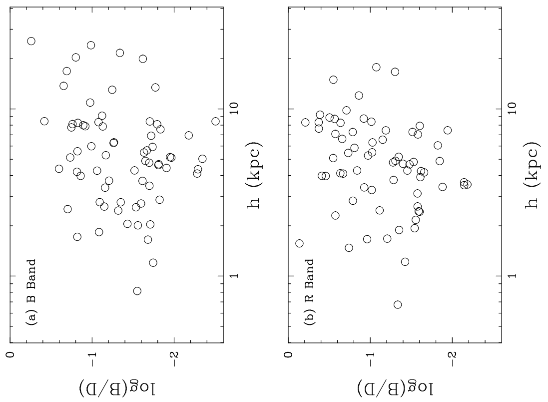


Fig. 2.— (a) The $B$-band bulge-to-disk luminosity ratios from galaxies in the upper envelope of Figure 1 (see text for details) are plotted against their associated disk scale-length. (b) The $R$-band data.

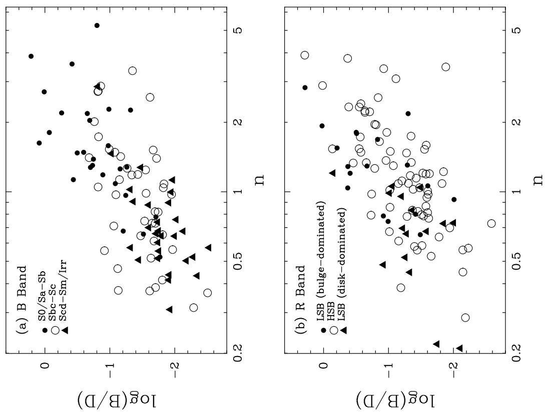


Fig. 3.— (a) The $B$-band bulge-to-disk luminosity ratios are plotted as a function of the $B$-band $r^{1/n}$ bulge shape parameter $n$. The points are labelled according to the host galaxy morphological type. (b) The $R$-band bulge-to-disk luminosity ratio are plotted as a function of the $R$-band $r^{1/n}$ bulge shape parameter $n$. The points are labelled according to the galaxy sample they came from. (Galaxies with no discernible bulge are not plotted.)