THE INFLUENCE OF BULGE PROFILE SHAPES ON CLAIMS FOR A SCALE-FREE HUBBLE SEQUENCE FOR SPIRAL GALAXIES

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ABSTRACT

We investigate recent claims that the Hubble sequence of spiral galaxies is scale-free. Fundamental to this investigation is the fact that within the photometric data of 86 spiral galaxies from de Jong & van der Kruit (1994) - from which these claims were made - a trend exists between morphological type and bulge profile shape. While late-type spiral bulges are described by an exponential luminosity profile, the early-type spiral bulges are better described by an $r^{1/2}$ or $r^{1/4}$ law. Taking the scale-lengths from the best-fitting surface brightness profile models (i.e. either using exponential, $r^{1/2}$, or $r^{1/4}$ law profile parameters), we show that in all six passbands used (BVRIHK) the early-type spirals have a larger r_e/h ratio than late-type spiral galaxies. In contrast to this, fitting an exponential profile to the bulges of all spirals results in the mean r_e/h ratio for the early-type spiral galaxies actually being smaller than the mean r_e/h ratio for the late-type spiral galaxies (at the 3σ significance level using K-band data).

Subject headings: galaxies: spiral, galaxies: structure, galaxies: fundamental parameters, galaxies: formation

1. Introduction

De Jong (1996b) and Courteau, de Jong, & Broeils (1996) have suggested that "the Hubble sequence of spirals is scale-free". They claim that "the constant ratio of bulge-to-disk scale-lengths appears to be independent of galaxy type". If true, this would not only be at odds with the classification scheme posed by Hubble (1926,1936) and later Sandage (1961) - in which the bulge-to-disk ratio progressively decreases as one goes from early to late type spirals (Simien & de Vaucouleurs 1986) - but would have consequences for theories of galaxy formation.

While the surface brightness profiles of the disks of spirals are well described by exponential models, the light profiles of the bulges are known to possess a range of structural shapes (Andredakis, Peletier & Balcells 1995; Carollo, Stiavelli & Mack 1998). These can be easily modelled with the Sersic (1968) $r^{1/n}$ law. A generalization of de Vaucouleurs' (1948) $r^{1/4}$ law, the free parameter n can describe the observed range of bulge profile shapes. Indeed, a subset of this model (namely n=1, 2, 4) was applied by de Jong (1996b) to the surface brightness profiles of the bulges in his sample of 86 face-on spiral galaxies. de Jong found that 60% of his sample were better modelled (based on the χ^2 statistic) with an n=1 model, while 40% preferred a larger value of n, with 15% preferring n=4. Similarly, Courteau (1996) found, when fitting both an n=1 and an n=4 profile model, that 15% of the bulges in his sample of spiral galaxies were better modelled with the n=4 profile (Courteau et al. 1996).

Given these results, Courteau et al. (1996) reported that late-type spirals are best fitted by two exponential models, and they chose to represent all their spiral galaxies this way. Subsequently, their claim for a scale-free Hubble sequence for spirals was based upon structural parameters ob-

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tained from fitting exponential light profile models to both the disk and the bulge.

However, the above percentages become most interesting when one notes that the galaxies preferring the larger values of n are the early-type spirals, while the late-type spirals prefer values of $n{\sim}1$ (Andredakis et al. 1995; Moriondo, Giovanardi, & Hunt 1998). Additionally, Andredakis et al. (1995) have shown that the bulge-to-disk ratio of luminosities varies systematically with profile shape, such that galaxies with larger bulge-to-disk luminosity ratio have larger shape parameters. Logically, any conclusions drawn from structural parameters which have ignored these structural differences must surely be questioned (Moriondo et al. 1998). By using the best-fitting profile models (either n=1, 2, or 4) this paper reinvestigates the claim for a scale-free Hubble sequence of spiral galaxies.

2. Data

We have re-analyzed the data presented by Courteau et al. (1996). They presented two data sets, however, only one is appropriate for explorations of galaxy properties as a function of morphological type.

Lahav et al. (1995) showed that the dispersion in galaxy type index, T, between six experienced galaxy classifiers was on average 1.8 T-units, and 2.2 T-units when comparing the RC3 (de Vaucouleurs et al. 1991) T-index with those of the six classifiers. A similar figure of disagreement (2.0-2.5 T-units) was obtained by four human classifiers of HST images (Odewahn et al. 1996). Unfortunately, because of this, the larger of the two data sets presented in Courteau et al. (1996) - 243 Sb–Sc galaxies from the 349 Sb–Sc galaxies of Courteau (1996) - can not in themselves be used to explore possible trends within the Hubble sequence of spiral galaxies.

What the R-band data of Courteau (1996) does enable, is to show that the individual ratios of bulge-to-disk scale-lengths span a broad range of values (Courteau et al. 1996, Figure 1). Scale-length ratios within just one standard deviation of the median are shown to span a range greater than a factor of 4, with the 1σ confidence interval ranging from 0.029 to 0.135, and a long tail in the distribution stretching to 0.35. To obtain the ratio of the bulge effective radius r_e to the disk scale-height h, these numbers should be multiplied by 1.679, giving ratios of r_e/h up to ${\sim}0.6$. Therefore, in passing, we stress that caution should be employed when using any sort of mean bulge-to-disk scale-length ratio, since a broad range of values spanning one order of magnitude exists amongst the real galaxy population.

The second data set, that of de Jong & van der Kruit (1994), is however useful. It includes galaxy types from Sa through to Sm. This sample of 86 galaxies actually includes two S0 galaxies which are removed here as de Jong (1996b) notes that their surface brightnesses are significantly below the trend seen for the rest of the spiral galaxies, and their connection with the early-type spiral galaxies is still unclear. The sole irregular galaxy (T=10) is also removed, leaving 83 face-on (minor over major axis ratios greater than 0.625) Sa to Sm galaxies, imaged in six passbands (BVRIHK).

3. Analysis

In recent years, some of the limitations of the classical surface brightness profile models, such as the exponential or the $r^{1/4}$ law, have been realised. Departures in the radial falloff of light from these models has been not only detected but successfully modelled for: the dwarf galaxy population (Davies et al. 1988; Young & Currie 1994; Binggeli & Jerjen 1998), the ellipticals (Caon et al. 1993; Graham & Colless 1997), brightest cluster galaxies (Graham et al. 1996), and for the bulges of spirals (Andredakis et al. 1995).

The Sersic (1968) law has proved successful in parameterizing such departures from the traditional models and can be written as

$$\begin{aligned} I(r) &= I_0 \exp\left[-\left(\frac{r}{h_b}\right)^{1/n}\right] \\ &= I_e \exp\left[-(2n-0.327)\left\{\left(\frac{r}{r_e}\right)^{1/n}-1\right\}\right]. \end{aligned} \quad (1)$$

The first line shows how the intensity I varies with radius r; I_0 is the central intensity where r=0. We use h_b here to denote the bulge scale-length and avoid confusion with the disk scale-length which is denoted by h elsewhere in this paper. The third model parameter, n, describes the level of curvature in the light profile. For example, when n=1 the Sersic law is equivalent to an exponential light distribution; when n=4 it mimics the de Vaucouleurs $r^{1/4}$ law. The value of n is of course not restricted to integer values and remains meaningful up until values of around 10-15. The second line is a variant of the first expression, with the model parameters now I_e, the intensity at the radius r_e which encloses half of the total light of the bulge. Equating like-terms, one has that I_0=$I_e\exp(2n-0.327)$ and (r_e/h_b)=$(2n-0.327)^n$. Therefore, when n=1, r_e=1.67h_b, and when n=2, r_e=13.5h_b. One can also easily see why effective radii rather than scale-lengths are used for the $r^{1/4}$ law, since h_b=$r_e/3466$. Given that this paper uses parameters from n=1, 2, and 4 Sersic models, we have used effective radii rather than scale-lengths.

de Jong (1996a) fitted three models to the surface brightness profiles of the bulges, all with an accompanying exponential profile model to the disk. The goodness-of-fit for each model was measured using the χ^2 statistic.[2] For the B, V, H and K passbands, it is observed that for every two galaxy bulges that are best fit with an n=2 or n=4 profile, there are three galaxy bulges whose best-fitting profile model is the n=1 model. For the R and I passbands, the number of galaxy bulges best fit with the n=1 model equal the number of bulges better fitted with the alternative n=2 or n=4 models (Table 1).

In using the best-fitting bulge models (either n=1, 2, or 4) the associated model parameters were not always reliable. In particular, the $r^{1/4}$ model sometimes resulted in values for r_e that were either inaccurately determined and/or were unrealistically large. To accommodate for this, each value of r_e was inspected and the galaxy either retained, or rejected if $\Delta r_e/r_e$>40% or r_e/r_{max}>0.5, where r_{max} is the maximum radius for which the the surface brightness profiles extend (∼26±1 in B). This typically resulted in the exclusion of only 1 or 2 galaxies from each of the morphological type bins T=1-3 and T=7-9 used in this comparative study.

Table 2 shows the difference in the mean value of r_e/h for the early- and late-type morphological class bins used by Courteau et al. (1996). It shows this ratio for the K- and R-band data fit with an exponential bulge model by de Jong (1996b) and Courteau et al. (1996). Using the best-fitting n=1, 2, and 4 models, we present this difference of means for all six passbands (BVRIHK). However, this difference in the ratio is meaningless on its own. What is important is the significance of this difference, and this depends on the sample size and standard deviation of the distributions. To this end, we have applied Student's t-test. The probability, Prob(t), that the difference in means could be as large as it is by chance is given in Table 2; small values indicate that the means are significantly different from each other.

4. Discussion

The majority of the early-type spirals (≤Sb) prefer to have values of n>1, while late-type galaxies (≥Sd) are better fit with an exponential bulge (see Table 1). The universal application of the exponential fitting function ignores from the start real differences in galaxy structure, and introduces a systematic bias into the parameterization of these galaxies - under-estimating the effective half-light radius of the bulge.[3] Figure 1 shows the ratio of the effective radii derived from the $r^{1/4}$ model ($r_{e,4}$) and the effective radii derived from the exponential model ($r_{e,exp}$), plotted against the ratio of the exponential model disk scale length co-fitted with the $r^{1/4}$ bulge model (h_4) and the exponential disk scale length co-fitted with the exponential bulge model (h_{exp}). It shows that $r_{e,4}/r_{e,exp}$>1, while the exponential disk scale-length remains largely unchanged as the bulge profile model is adjusted.

Similarly, fitting an n=1 profile will over-estimate the half-light radii for some of the late-type spirals. Although de Jong (1996a) shows for the late-type spirals that an n=1 model provides a better representation of the bulge than an n=2 or n=4 model, he also notes that values as low as n=0.5 are obtained when applying the Sersic profile to the bulge (de Jong 1996a). Furthermore, Andredakis et al. (1995), in fitting the Sersic model to the K-band bulge light profiles of 30 spiral galaxies, found some Sb–Sd galaxies to

[2]The data can be found at http://cdsweb.u-strasbg.fr/htbin/Cat?J/A+AS/118/557.

[3]A similar behaviour is known to occur with $r^{1/4}$ modelling of the light profiles of elliptical galaxies (Graham & Colless 1997, Figure 11).

have bulge profiles with shape parameters smaller than 1. Consequently, restricting the structural profiles of all late-type galaxies to be described by an n=1 model may be increasing their mean bulge scale-length and hence reducing the true difference between the r_e/h ratio of the early- and late-type spirals. That is, the probabilities in Table 2 may be larger than they should.

As stated by de Jong (1996b), K-band data is the passband of choice for such studies, making it "possible for the first time to trace fundamental parameters related to the luminous mass while hardly being hampered by the effects of dust and stellar populations." Indeed, some of the galaxies in de Jong sample were noted to possess dust lanes and circumnuclear star formation. Furthermore, bulges are brighter in K than in B with respect to the disk, and since the bulge/disk decomposition is easier when the bulge is relatively brighter, the fitting algorithm therefore works better in the K-band (de Jong 1996b).

Using exponential bulge models, Courteau et al. (1996) mention that the r_e/h ratios of the early-type spirals appear systematically below the average r_e/h value for all spiral galaxy types. They assert that this difference is not large, and claim that the constant ratio of bulge-to-disk scale-length is independent of Hubble type. However, our analysis of the exponential models fitted to the K band data of de Jong (1996b, Figure 18) reveals that the mean value of r_e/h for the Sa–Sb type galaxies is actually smaller than that for the late-type spirals at a significance of 98% (3σ)! (Table 2). Similarly, with the R-band data presented by Courteau et al. (1996), and in fact for all wavelengths used (excluding the V-band), the ratio of r_e/h is smaller for the Sa–Sb galaxies than it is for types $\geq$Sbc. This result is at odd with the classical picture of the Hubble sequence, where early-type spirals have larger bulge-to-disk scale-length ratios than late-type spirals.

Due to the use of exponential bulge models for the Sa–Sb type galaxies, the above result can be understood in terms of systematically underestimating the size of these bulges. Correcting for this, by taking the best-fitting structural parameters, from either the n=1, 2, or 4 models, we find that the situation reverses itself. The average value of r_e/h for the Sa–Sb type galaxies is found to be larger than the average value of r_e/h for galaxy types $\geq$Sd, in all six passbands. Table 2 shows that the probability that the Sa–Sb type galaxies have the same mean r_e/h as the Sd–Sm type galaxies is weakly ruled out at the 1.5–2 σ level in five of the six passbands used by de Jong & van der Kruit (1994). Interestingly, it is the K-band data which suggest that the difference in means is not significant. However, this result in itself is significant when compared to the result obtained using only exponential bulge profile models. Using the best-fitting models, the average r_e/h ratio for the sample is larger – at the 3 σ significance level – than when obtained using only the n=1 model.

We plan to refine this work by fitting a Sersic profile with free (i.e. not fixed) shape parameter, n, to the bulges of the spirals in the sample of de Jong & van der Kruit (1994). Furthermore, Courteau et al. (1996) noted that about 1/3 of the sample of galaxies from de Jong (1996a) had a bar modelled as an additional component - requiring eight structural model parameters for these galaxies. While de Jong modelled a bar when fitting the exponential bulge models to the 2D images, his one-dimensional decomposition technique which he used to fit the $r^{1/4}$ and $r^{1/2}$ bulge models did not allow for the influence of a bar. Subsequently, we must caution that failure to model the bar in the 1D data used here may influence the scale-lengths obtained.

Arguments for secular evolution, namely the exponential bulge light profile and the restricted range of bulge-to-disk scale-lengths, are either wrong or questionable. Andredakis et al.'s (1995) alternative to secular evolution - based upon the continuous trend between galaxy structure, as measured by n, and galaxy type - is largely supported by the data of Courteau et al. (1996). In the framework of this model, n-body simulations (Andredakis 1998) have shown how the imprint of disk formation is left upon the bulge, creating the observed trend between shape parameter and morphological type. Yet another alternative is offered by Aguerri & Balcells (1999), where the shape of the bulge grows from an n=1 profile to larger values of n as shown through n-body simulations of merger events.

Whether the bulges of spiral galaxies formed after the disk, as in the secular evolution model (Courteau et al. 1996), or, whether the bulge is in fact older than the disk (Andredakis 1998, and references within) may be better answered when the range and trends of bulge-to-disk ratios are better known.

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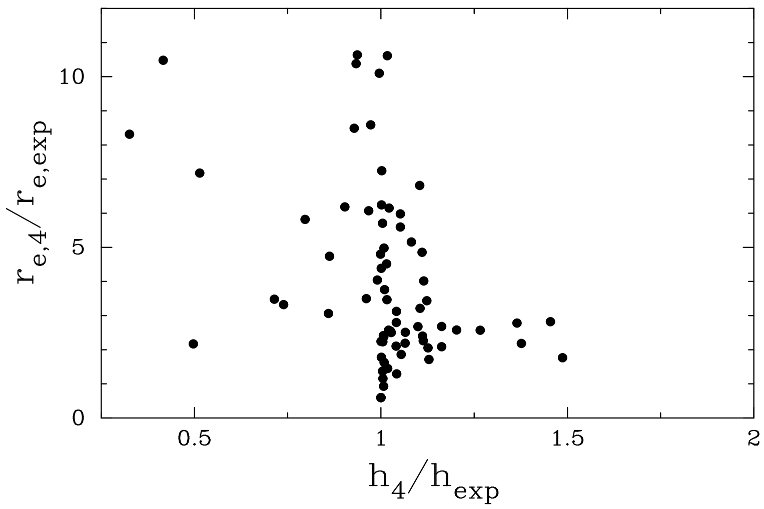

Fig. 1.— For each galaxy, the value of r_e from the n=4 bulge model, divided by the value of r_e from the n=1 bulge model, is plotted against the corresponding ratio of h from the two associated exponential disk models. While the scale-length of the exponential disk remains largely unchanged, the effective radius of the bulge is shown to be larger with an $r^{1/4}$ bulge model than with an exponential bulge model. (K-band data.)

TABLE 1
BEST-FITTING BULGE MODELS

Morphological Type	No. of galaxies best fit with each model Exponential	$(r^{1/2}, r^{1/4})$	(no data)
	B-band		
Sa,Sab,Sb	10	12	0
Sbc,Sc,Scd	31	16	1
Sd,Sdm,Sm	11	2	0
	V-band		
Sa,Sab,Sb	7	8	7
Sbc,Sc,Scd	24	18	6
Sd,Sdm,Sm	10	2	1
	R-band		
Sa,Sab,Sb	6	16	0
Sbc,Sc,Scd	25	21	2
Sd,Sdm,Sm	10	3	0
	I-band		
Sa,Sab,Sb	5	11	6
Sbc,Sc,Scd	21	24	3
Sd,Sdm,Sm	10	3	0
	H-band		
Sa,Sab,Sb	6	8	8
Sbc,Sc,Scd	13	5	30
Sd,Sdm,Sm	4	2	7
	K-band		
Sa,Sab,Sb	8	13	1
Sbc,Sc,Scd	27	18	3
Sd,Sdm,Sm	12	1	0

NOTE.—This table lists the number of spiral galaxy bulges whose surface brightness profiles are best fit with an exponential model, and the number of galaxy bulges that are better modelled with the alternative ($r^{1/2}$ or $r^{1/4}$) profile. The fourth column displays the number of galaxies for which no χ^2 goodness-of-fit estimate was available. χ^2 data taken from de Jong (http://cdsweb.u-strasbg.fr/htbin/Cat?J/A+AS/118/557).

TABLE 2

COMPARISON OF THE r_e/h DATA DISTRIBUTIONS

Band	$\langle \frac{r_e}{h} \rangle_1 - \langle \frac{r_e}{h} \rangle_2$	Prob(t)
	Exponential bulge model data	
	1:(S0,Sa,Sab,Sb) vs. 2:(Sbc,Sc,...Sm,Irr)	
K-band	(0.119-0.162)=–0.043	02%
R-band	(0.112-0.124)=–0.012	34%
	Exponential bulge model data	
	1:(Sa,Sab,Sb) vs. 2:(Sd,Sdm,Sm)	
K-band	(0.118-0.195)=–0.077	03%
R-band	(0.111-0.126)=–0.015	52%
	Best-fitting bulge models	
	1:(Sa,Sab,Sb) vs. 2:(Sd,Sdm,Sm)	
K-band	(0.240-0.228)=+0.012	79%
H-band	(0.485-0.173)=+0.312	07%
I-band	(0.348-0.190)=+0.158	24%
R-band	(0.333-0.186)=+0.147	23%
V-band	(0.671-0.161)=+0.510	14%
B-band	(0.321-0.160)=+0.161	18%

NOTE.—Comparison of the r_e/h data distributions for different morphological-type bins. Column 1 shows the passband used. The difference between the mean values from the two distributions (as listed 1: and 2: in the table sub-headings) is shown in column 2. Column 3 gives the significance that the two distributions have the same mean value, as derived from Student's t-test and allowing for different population variances between the two data sets. Small probabilities indicate that the data sets are different.