

EVIDENCE FOR SECULAR EVOLUTION IN LATE-TYPE SPIRALS

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ABSTRACT

We combine deep optical and IR photometry for 326 spiral galaxies from two recent galaxy samples and report that the surface brightness profiles of late-type spirals are best fitted by two exponentials. Moreover, the ratio of bulge and disk scale lengths takes on a restricted range of values and is uncorrelated with Hubble type. This suggests a scale-free Hubble sequence for late-type spirals. Careful numerical simulations ensure that our results are not affected by seeing or resolution effects. Many of these galaxies show spiral structure continuing into the central regions with a previously undetected small bar and slowly changing colors between the inner disk and the bulge. We invoke secular dynamical evolution and interpret the nature of disk central regions in the context of gas inflow via angular momentum transfer and viscous transport. In this scenario, galaxy morphologies in late-type spirals are not imprinted at birth but are the result of evolution.

Subject headings: galaxies: formation — galaxies: photometry — galaxies: spiral — galaxies: structure

1. INTRODUCTION

Recent infrared observations suggest that spiral galaxies may exhibit a greater fraction of bars than was once inferred from (nuclear-saturated) optical data (Block & Wainscoat 1991; Zaritsky, Rix, & Rieke 1993). Optical surveys already reveal that $\sim 2/3$ of disk galaxies have a bar (Sellwood & Wilkinson 1993; Martin 1995). Indeed, it is believed that most spirals have probably harbored a self-destructive bar at one time or another during their evolution (Friedli & Benz 1993, hereafter FB93; Friedli, Benz, & Kennicutt 1994). Such bars are easily formed through global instabilities of a rotationally supported disk or via interactions, and gas redistribution by the bar can cause its own dissolution. Box- or peanut-shaped bulges also provide evidence for the current existence of a bar in edge-on systems. Once formed, such bars or oval distortions are believed to be efficient carriers of disk material into the central regions through angular momentum torques and viscous transport (Kormendy 1993, hereafter K93; Pfenniger 1993, hereafter P93; Martinet 1995, hereafter M95; and references therein). Viscous dissipation has been proposed by many (Silk & Norman 1981; Lin & Pringle 1987; Yoshii & Sommer-Larsen 1989; Saio & Yoshii 1990; Struck-Marcell 1991, hereafter SM91) to explain the exponential distribution of the stars in galactic disks. An exponential profile in the central regions is also expected from nonaxisymmetric disturbances that will induce inward radial flow of disk material (Combes et al. 1990; Pfenniger & Friedli 1991; SM91; P93).

While common use of the $r^{1/4}$ law (de Vaucouleurs 1948) for

fitting the light profile of disk central regions has endured unprecedented popularity over the years, evidence for exponential falloff of the central light distribution (or at least departures from $r^{1/4}$) in disk galaxies is not recent (van Houten 1961; Frankston & Schild 1976; Kormendy & Bruzual 1978; Burstein 1979; Shaw & Gilmore 1989; Kent, Dame, & Fazio 1991; Andredakis & Sanders 1994). Recently, Andredakis, Peletier, & Balcells (1995, hereafter APB) used the generalized exponential law of Sérsic (1968) with their images for 30 early-type spirals and data from Kent (1986) for 21 late-type systems to show that bulge profiles vary with Hubble types. Sérsic proposed the form

$$\Sigma(r) = \Sigma_0 \exp[-(r/r_0)^{1/n}],$$

where Σ_0 is the central surface brightness (CSB), r_0 is a scaling radius, and n is the exponent variable. If $n = 1$, one has a pure exponential profile with r_0 as the scale length; with $n = 4$, one recovers a de Vaucouleurs profile.

In this Letter, we use the red and infrared light profiles for 326 spirals to confirm the result by APB that central regions of late-type spirals are best fitted by an exponential and separately show that the bulge and disk scale lengths are closely coupled. Unlike APB, we interpret these results as support for a picture of secular evolution in disk galaxies.

2. METHOD

We have combined the large collection of deep r -band profiles of Sb/Sc galaxies by Courteau (1992; 1996, hereafter C96) and *BVRHK* photometry by de Jong (1995, hereafter dJ95) for face-on Sa–Sm galaxies. Courteau's sample was selected for Tully-Fisher mapping of peculiar velocities and thus includes galaxies of moderate to high inclinations ($50^\circ < i < 80^\circ$). The original collection counts 350 spirals, but 290 were kept for final decompositions; the others were too

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small to successfully resolve the bulge. Sky subtraction errors, probably the greatest source of uncertainty in bulge-to-disk (B/D) decompositions, were investigated and treated with great care (C96). De Jong's sample was constructed to examine the global structure of spiral galaxies including the elusive law of constant disk CSB (Freeman 1970; dJ95; McGaugh, Bothun, & Schombert 1995; C96) and to study the observable effects of dust and stellar populations in spirals. The IR data are extremely useful for studying the central light, unobscured by the dust; profile decomposition is thus less likely to suffer from internal absorption effects (Phillips et al. 1991). Moreover, the wide sampling of Hubble types allows one to examine morphology correlations. Both samples were selected from the UGC (Nilson 1973) and include only systems with normal-looking appearances and clean stellar foreground. The typical galaxy size is 2'.3. Many of these galaxies were classified as nonbarred by Nilson, but direct examination of the IR image or removal of a smooth bulge and disk fit from the optical image often reveals the presence of a bar. About one-third of de Jong's galaxies required a bar as an extra component to fit the surface brightness distribution.

B/D decompositions were done independently by de Jong (dJ95, 1996) and Broeils & Courteau (1996, hereafter BC96). We combine our results for the benefit of this Letter. Unfortunately, no overlap exists between the two catalogs to test for systematic errors. dJ95 used both major-axis profiles (one-dimensional) and full image (two-dimensional) B/D decompositions of his thesis sample with $n = 1, 2$, and 4 for the central regions and a standard disk exponential. Two-dimensional decompositions offer the advantage of fitting for any additional central component such as a bar, ring, or lens. They also yield smaller error bars than one-dimensional decompositions on each of the fitted parameters and allow for a more robust recovery of simulated input parameters (Byun & Freeman 1995; dJ95). Still, we find that our results do not depend strongly on the type of techniques adopted.

BC96 decompose the light profile of Courteau's galaxies as bulges with $n = 1$ and 4, plus an exponential disk. This one-dimensional technique is similar to that introduced by Kormendy (1977), which consists in χ^2 -fitting the bulge and disk profiles simultaneously via nonlinear least-squares analysis. Two-dimensional decompositions for the same galaxies, in a study of correlations with the rotation curve, will be presented elsewhere (Courteau & Broeils 1996). While dust is more conspicuous at r than K for central regions, we believe that our results are not significantly affected by dust since they statistically reproduce the same range of values for de Jong's galaxies in the K -band. In all cases, seeing is accounted for by convolving the model profiles with a Gaussian point-spread function (PSF) with a dispersion measured from field stars.

Since bulges of late-type spirals are small and can be affected by atmospheric blur, we tested our decomposition routines with thousands of artificial images (or surface brightness profiles in one dimension) with a wide range of input parameters and various values of n to derive a space of recoverable parameters (see also Schombert & Bothun 1987; Byun & Freeman 1995; and APB). The simulated images were convolved with a seeing Gaussian and include photon and readout noise. Our results suggest that all values of r_b above 1" are successfully recovered for all observed seeing values, as are the values between 0".5 and 1".0 with a seeing disk below 2". Values of $r_b < 0".5$ – $0".6$ are not reliable unless seeing is better than 1".5. In light of these results, we reduced Courteau's sample to 243 galaxies. The measuring uncertainty in CSBs

and scale lengths is dominated by sky subtraction errors. Full details are given in dJ95 and BC96.

3. RESULTS

From examination of the reduced χ^2 values, we find that most late-type spirals are best fitted by a double exponential. Sixty percent of de Jong's total sample, which includes most of the Sb and Sc galaxies and all galaxies of later type, is best modeled with the double exponential. A quarter of the sample, mostly Sa's–Sab's, is best modeled with a $n = 2$ bulge. Few galaxies ($\sim 15\%$) are more appropriately fitted by a de Vaucouleurs law in the central regions. BC96 find that about 85% of their Sb's and Sc's are best fitted by the double exponential, while the remainder is better fitted with an $r^{1/4}$ bulge profile. Granted that $n = 1$ for most late-type spirals, we adopt exponential profiles for the central region and disk of all galaxies in our sample and compute their scale length ratio.⁴ Figures 1 and 2 show the measured scale lengths for our divided sample in the r -band. The inset histograms show the range of possible values for the scale lengths' ratio. Displayed in physical units, the correlation would show a slightly narrower stretch from 0 to 10 kpc (dJ95). Angular units show that the correlation is not affected by resolution effects.

Combining both r -band data sets, we find $r_b/r_d = 0.08 \pm 0.05$, while de Jong galaxies alone at K' yield $r_b/r_d = 0.09 \pm 0.04$ (not shown). Hence, the effect of dust is not alarming. Results at B or V are not presented because the scatter becomes too large. Note also that this result would remain unnoticed were one to fit (inappropriately) all the inner regions with an $r^{1/4}$ law. The histogram peak value may not be determined with great certainty (2σ), but the importance of Figures 1 and 2 is the demonstration of a restricted range for the scale length ratio. Earlier type spirals (Sa's–Sab's) in Figure 2 appear systematically below the nominal line as a result of "improper" fitting of an $n = 1$ bulge profile. Nonetheless, the discrepancy is not large, and early-type spirals closely follow the overall trend, which suggests that the Hubble sequence of spirals is scale free. While each Hubble type comes with a range of different diameters and total luminosities, the constant ratio of B/D scale lengths appears to be independent of galaxy type. Disks of larger scale lengths would simply form bulges with correspondingly larger scale lengths.

4. DISCUSSION

A correlation between B/D scale lengths is best understood in a model where the disk forms first and the bulge that naturally emerges is closely coupled to the disk. Were the bulge to form first, it would be hard to understand how a small, dynamically hot component could directly influence the disk global structure. In standard cosmological models, galaxy formation occurs when matter decouples from the uniform Hubble flow and a disk (for spirals) is formed by dissipational collapse of the initial gas. The observations presented here concern the stellar component of central galactic regions, and the main obstacle in making the bridge between the phase of formation and current observations is the limited numerical resolution and ad hoc formulation that bulge stars form from primordial high- σ fluctuations (Katz 1992; Navarro & White 1993; Steinmetz & Müller 1994). The secular evolution models in which the bulge is formed naturally from the disk have more predictive power. In a model of viscous evolution, an expo-

⁴ The results are unchanged if we restrict ourselves to the subsample of pure $n = 1$ central profiles only.

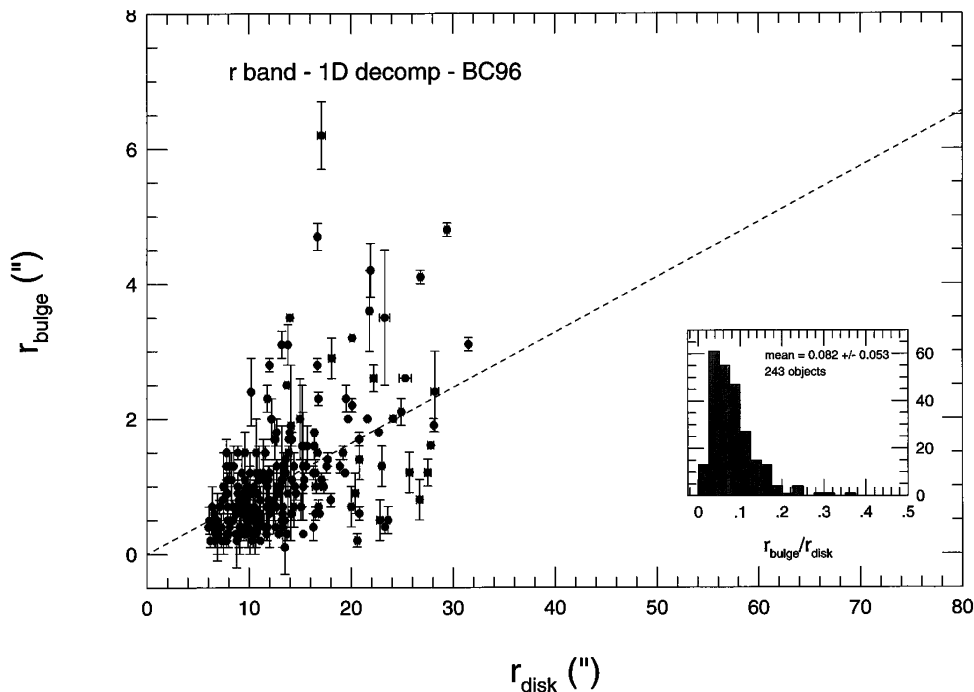


FIG. 1.—Fitted scale lengths for the bulge and disk in arcseconds from BC96 for 243 Sbc and Sc galaxies in Courteau’s sample (C96). The dashed line is a fit to the data; its slope is given by the mean ratio of $r_{\text{bulge}}/r_{\text{disk}}$. The histogram shows the distribution of B/D ratio (unweighted by the errors).

nential disk emerges from the redistribution of angular momentum by the viscosity of the gas, if star formation occurs on roughly the same timescale (Lin & Pringle 1987; Yoshii & Sommer-Larsen 1989; SM91). Such a model will automatically develop a “bulge” whose properties depend only on the relative timescales of star formation and viscous transport and on the total angular momentum (Combes et al. 1990; Saio & Yoshii 1990; SM91) and will produce correlated B/D scale

lengths. Efficiency of transport will be improved with a bar or oval distortion that can be triggered by a global dynamical instability in the disk or induced by interactions with a satellite (M95). This, in turn, will induce funneling of disk material into the central regions. Disk stars will be heated vertically up to 1–2 kpc above the plane by resonant scattering off of the bar-forming instability, and a “bulgelike” component with a nearly exponential profile will emerge due to relaxation in-

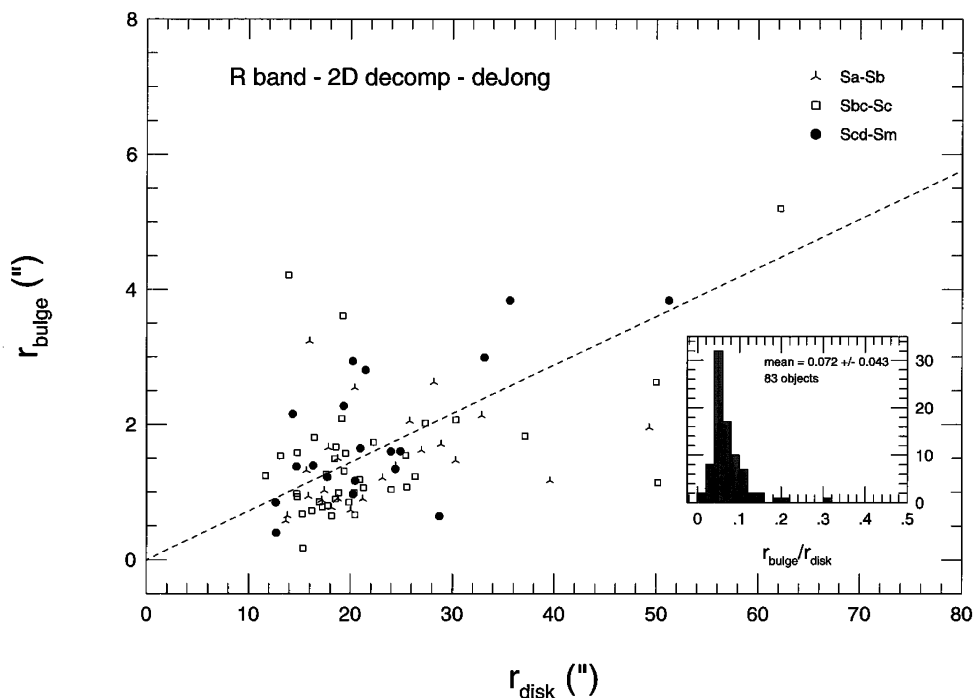


FIG. 2.—Same as Fig. 1 for de Jong’s galaxies. The different symbols represent different ranges of Hubble types. The formal fit error bars for these two-dimensional decompositions (not including sky uncertainties) are comparable to the size of each point and were not plotted to preserve clarity.

duced by the bar (K93, P93, and references therein). Secular accumulation or satellite accretion of only 1%–3% of the total stellar disk mass near the center is sufficient to induce dissolution of the bar into a spheroidal component (Pfenniger & Norman 1990; Friedli 1994; M95). Secular evolution with bar transport can thus be a viable explanation for bulge formation in late-type spirals whether a bar is or is no longer present.

Our measurements of exponential stellar density profiles as well as a restricted range of B/D scale lengths provide strong observational support for secular evolution models. Self-consistent numerical simulations of disk galaxies evolve toward a double-exponential profile with a typical ratio between bulge and disk scale lengths near 0.1 (D. Friedli 1995, private communication) in excellent agreement with our measured values. Circumstantial evidence also includes the color of bulges, which is known to change only slowly from the inner disk into the central regions (Courteau & Holtzman 1995, 1996; dJ95; Peletier & Balcells 1995), and the fact that, unlike ellipticals, bulges' kinetic energy comes mostly in rotation, which must be imparted from the disk (Kormendy 1985; P93). Subtraction of an elliptical profile fit from the original galaxy image shows residual spiral structure that extends all the way into the center of the galaxy for the majority of Courteau's galaxies. This provides further support (although not absolute evidence) for an association between the bulge and disk (K93; Zaritzky et al. 1993).

Note that APB reject secular evolution on the basis of their continuous spectrum of the index n versus morphological type. They propose that the smooth sequence they observe (see their Fig. 5) can only result from a single mechanism of bulge formation. Given the large scatter in their diagram, such a conclusion seems ill based. A more plausible scenario in which big bulges (>2 kpc as in Sa's) form principally from a minor merger and smaller bulges (1–2 kpc; Sd's \rightarrow Sab's) form mainly via secular evolution is not likely to leave any bimodal imprint on the spectrum of " n " as both processes will operate to some degree of efficiency for all Hubble types⁵ (P93; M95).

Chemical evolution is also likely to be affected by gas flows in the center of galaxies. For galaxies undergoing central star formation bursts, Friedli et al. (1994) show that the gas-phase abundance gradient should be characterized by two separate slopes corresponding to the inner and outer regions of the disk. We expect that the break point will correlate with the transition between the central and outer disk exponentials. This remains to be tested. A metallicity-velocity dispersion relation for the core is expected as well, although current nuclear stellar abundances are too uncertain to provide conclusive evidence (Friedli & Benz 1995). Boroson (1980) measured central metallicities (Mg₂ index) in the bulge of 24 spirals and found a higher correlation with bulge light than with total light though with poor statistics (see also Jablonka, Martin, & Arimoto 1995). Such a picture, if true, would suggest a decoupling of the bulge and disk at formation, in stark contrast with models of secular evolution. Finally, the possible existence of an intermediate-age population with some ongoing star formation in the bulges of our Galaxy, M31, and M32 (Davies, Frogel, & Terndrup 1992; Rich, Mould, & Graham 1993; see also Renzini 1993) would lend support to secular evolution models.

Tests for secular evolution will greatly benefit from the measurement of high-resolution central abundances and metallicity gradients coupled with studies of the two-dimensional infrared light distribution to fit the exponent n for a large sample of Sd's–Sa's. Nearby and more distant samples are needed to test for the effects of galaxy evolution.

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⁵ The observed scatter in both APB's Fig. 5 and our Figs. 1 and 2 is probably correlated with some third parameter that could provide a link between secular evolution and merging scenarios. This will be investigated elsewhere.

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