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# CONSTRAINTS ON BULGE FORMATION SCENARIOS

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RESUMEN

Se han analizado los parámetros estructurales galácticos por técnicas robustas, con base en modelos de la morfología y el brillo de los bulbos y los discos, y utilizando un conjunto de datos multibanda (BVRH) para 121 galaxias espirales tardías cercanas. Cada perfil de luminosidad se descompuso en un bulbo generalizado de Sersic y un disco exponencial. Se estudia el conjunto final de parámetros galácticos para encontrar variaciones y correlaciones en el contexto de diferencias en el tipo de perfil y dependencias de la longitud de onda. El parámetro de Sersic para la forma del bulbo de las galaxias espirales tardías de tipo I tiene valores entre 0.1 y 2, si bien, en promedio, el perfil de densidad subyacente para el bulbo concuerda con una distribución exponencial. El cociente de los tamaños de los bulbos y discos está acoplado, y satisface $\langle r_e/h \rangle = 0.22 \pm 0.09$, independientemente de la longitud de onda y del tipo de Hubble. Interpretamos este resultado como evidencia de una formación regulada del bulbo mediante la redistribución del material del disco hacia el centro galáctico, en concordancia con los modelos de formación de barras por inestabilidades en el disco.

ABSTRACT

A robust analysis of galaxy structural parameters, based on the modeling of bulge and disk shapes and brightnesses, was performed on a multi-band (BVRH) data set of 121 nearby late-type spirals. Each luminosity profile is decomposed into a generalized Sérsic bulge plus an exponential disk. The final set of galaxy parameters is studied for variations and correlations in the context of profile type differences and wavelength dependences. The Sérsic bulge shape parameter for nearby Type-I late-type spirals shows a range between $n = 0.1$–$2$ though, on average, the underlying surface density profile for the bulge is consistent with an exponential distribution. The size ratios of bulges and disks are coupled with $\langle r_e/h \rangle = 0.22 \pm 0.09$, independent of wavelength and Hubble type. We interpret this result as evidence for regulated bulge formation by redistribution of disk material to the galaxy center, in agreement with models of bar forming instabilities of the disk.

*Key Words:* **GALAXIES: FORMATION — GALAXIES: PHOTOMETRY — GALAXIES: SIMULATIONS — GALAXIES: SPIRAL — GALAXIES: STRUCTURE**

## 1. INTRODUCTION

Stellar density distributions provide important constraints for bulge and disk formation models. While the exponential nature of the brightness profile of disks has been long established, it is becoming clear that the light profiles of bulges exhibit a range in shape, characterized by the shape parameter $n$ of the Sérsic law, from early- to late-type galaxies (e.g. Graham 2001). The observed range in bulge shapes and structural correlations between the bulge and disk provide fundamental constraints for structure formation models. Our study (see MacArthur et al. 2002) focuses on the development of a reliable set of observables and constraints for such models through reliable modeling of bulge and disk parameters from surface brightness (SB) profile decompositions on a large multi-wavelength sample of late-type spiral galaxies. We aim to characterize and quantify the intrinsic structural properties of the bulge and disk and the extent of their variation with wavelength. Multi-wavelength information provides insight about structural variations within and among galaxies due to dust and stellar population effects.

## 2. THE DATA

We used a sub-sample of 121 non-disturbed galaxies from our multi-band catalog of UGC late-type galaxies with face-on and intermediate inclinations. Barred galaxies, as classified in the UGC, were not excluded *per se* but only a handful were observed. Most galaxies have at least one set of BVRH images and multiple observations for 54 galaxies are used to estimate systematic errors. The profiles typically reach below 26 BVR and 22 H-mag arcsec$^{-2}$.

## 3. SURFACE BRIGHTNESS PROFILES

The traditional description of the radial SB profile of spiral galaxies is the sum of a bulge and exponential disk components. Two types of SB pro-

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files are normally defined: Type-I/II if the bulge-disk transition region lies above/below the inward disk extrapolation. We also define a third "transition" type for profiles that change from Type-II at optical wavelengths to Type-I in the infrared. In addition, we observe that many galaxies classified as Type-II show a weakening of the inner profile dip at longer wavelengths.

N-body simulations (e.g. Norman, Sellwood, & Hasan 1996; Valenzuela & Klypin 2002) reproduce Type-II surface density profiles as a result of the redistribution of central stars into a ring by a bar-like perturbation. Galaxy centers may recurrently change from a barred to an unbarred phase and undergo continuing bulge building as the bars dissolve. Thus, the paucity of barred galaxies in our sample does not preclude bar-induced effects as a possible explanation for Type-II profiles. Pre-existing bars may simply have dissolved. Furthermore, out of 8 barred galaxies in our sample, 6 have Type-II profiles, thus lending credence to the bar-lens scenario. Alternatively, Type-II profiles may also be explained by extinction effects in the disk, as shown by Evans (1994) with models using exponential distributions of stars and dust.

## 4. B/D DECOMPOSITION TECHNIQUE

We model bulge and disk components simultaneously as generalized Sérsic and exponential profiles respectively, using 1D and 2D non-linear $\chi^2$ minimization routines. The bulge and disk model functions are convolved with a Gaussian PSF (with appropriate seeing FWHM). Surface brightnesses with random errors greater than 0.12 mag arcsec$^{-2}$ are excluded. We have tested the reliability of our B/D decompositions with extensive simulations (MacArthur et al. 2002).

## 5. RESULTS

- Sky/seeing error estimates and the choice of disk spatial extent and bulge shape can cause significant errors (>50%) in the measurement of galaxy parameters. B/D decompositions of Type-I profiles yield bulge and disk scale parameters with errors less than 20% and 5% respectively.
- There is a significant trend of decreasing scale length with increasing wavelength (also found in de Jong 1996), indicative of a higher concentration of older stars and/or dust in the central regions relative to the outer disk.
- The Sérsic bulge shape parameter for nearby late-type galaxies shows a range between $n = 0.1 - 2$, but, on average, their underlying SB distribution is best described by an exponential ($n = 1$) model.
- We confirm and reinforce the finding by Courteau, de Jong, & Broeils (1996) of a structural coupling between the bulge and disk of HSB spirals. We find $\langle r_e/h \rangle = 0.22 \pm 0.09$, or $\langle h_{\rm bulge}/h_{\rm disk} \rangle = 0.13 \pm 0.06$, independent of wavelength. Including de Jong's (1996) catalogue of S0–Sd galaxies, this result is also independent of Hubble type (see also Graham 2001).

A natural interpretation of the near constancy of B/D size ratios in late-type spirals is that their bulges formed via secular evolution of the disk. This scenario is possible if disks are bar-unstable, which can be triggered by the global dynamical instability of a rotationally supported disk or induced by interactions with a satellite and if significant angular momentum transport is feasible (e.g. Martinet 1995).

Recent cold dark matter hierarchical hydrodynamical simulations (Saiz et al. 2001; Scannapieco & Tissera 2002, in prep.) show that secular processes can occur naturally during the formation of spiral disks and play an important role in the regulation of star formation and the determination of the dynamical and structural properties of these systems. On average, the simulated disk systems are shown to be characterized by a double exponential profile which naturally emerges within the hierarchical clustering scenario. The distribution of final Sérsic $n$ parameters for relaxed present-day late-type disks from the models of Scannapieco & Tissera (2002, in prep.) reproduce our results nicely.

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