GALACTIC BULGES FROM HUBBLE SPACE TELESCOPE NICMOS OBSERVATIONS: THE LACK OF $R^{1/4}$ BULGES

MARC BALCELLS, ALISTER W. GRAHAM, LILIAN DOMÍNGUEZ- PALMERO
Instituto de Astrofísica de Canarias, 38200 La Laguna, Tenerife, Spain
balcells@iiaiac.es

AND

REYNIER F. PELETIER
School of Physics and Astronomy, University of Nottingham, NG7 2RD, UK

ABSTRACT

We use Hubble Space Telescope (HST) near-infrared imaging to explore the shapes of the surface brightness profiles of bulges of S0-Sbc galaxies at high resolution. Modeling extends to the outer bulge via bulge-disk decompositions of combined HST - ground based profiles. Compact, central unresolved components similar to those reported by others are found in ~84% of the sample. We also detect a moderate frequency (~34%) of nuclear components with exponential profiles which may be disks or bars. Adopting the Sérsic $r^{1/n}$ functional form for the bulge, none of the bulges have an $r^{1/4}$ behaviour; derived Sérsic shape-indices are $n > 1.7 ± 0.7$. For the same sample, fits to NIR ground-based profiles yield Sérsic indices up to $n = 4 – 6$. The high-$n$ of ground-based profiles are a result of nuclear point sources blending with the bulge extended light due to seeing. The low Sérsic indices are not expected from merger violent relaxation, and argue against significant merger growth for most bulges.

Subject headings: galaxies:spiral — galaxies:structure — galaxies:nuclei — galaxies:fundamental parameters — galaxies:photometry

1. INTRODUCTION

Whether galaxy mergers (e.g. Kauffmann et al. 1996) or instead disk instabilities (Pfenniger & Norman 1990) may be viewed as the dominant process of formation and growth of the central bulges in spiral and S0 galaxies depends to some extent on the shape of the surface brightness profiles of bulges. Simulations of mergers of similar-size galaxies yield spheroidal systems following the $r^{1/4}$ law (e.g. Barnes 1988). The accretion of dense satellites onto bulge-disk galaxies also leads to $r^{1/4}$ bulges (Aguerri, Balcells & Peletier 2001, hereafter ABP01). In contrast, disk instabilities lead to bulges with approximately exponential profiles (Combes et al. 1990).

Over the past decade several studies have stressed that bulges of late- to intermediate-type spiral galaxies are best fit with profiles of exponential to $r^{1/2}$ shapes (Andredakis & Sanders 1994; de Jong 1996; Courteau, de Jong & Broeils 1996; Seigar & James 1998; Carollo, Stiavelli & Mach 1998; MacArthur et al. 2002). However, many bulge-disk decompositions are still performed using $r^{1/4}$ bulges only, especially at high-z, e.g. Simard et al. (2002); the $r^{1/4}$ law is often cited for massive or early-type bulges: Carollo and collaborators (e.g. Seigar et al. 2002 and references therein) routinely classify bulges into $r^{1/4}$ and exponential types. Do massive bulges follow the $r^{1/4}$ model? Do bulges come in two flavors, perhaps pointing at massive bulges growing by early mergers and less-massive bulges growing by disk instabilities?

Fitting bulge profiles with the Sérsic model $\mu(r) \sim r^{1/n}$ provides an avenue for measuring the true shapes and concentrations of the light distribution of bulges. Various studies that include early-type bulges (Andredakis, Peletier & Balcells 1995, hereafter APB95; Khosroshahi et al. 2000; Graham 2001; Möllenhoff & Heidt 2001) find a continuous distribution of Sérsic shape indices $n$ that scales with bulge luminosity from $n < 1$ to $n > 4$. At the high-$n$ end, these results depend strongly on the innermost regions of the profiles. Inner disks, compact sources and star formation, present in galaxy nuclei (e.g. Phillips et al. 1996; Carollo et al. 2002; Rest et al. 2001; Pizzella et al. 2002), contribute light that cannot be disentangled from the spheroid light at ground-based resolutions (Ravindranath et al. 2001). Extra central light results in higher-$n$ profile fits.

Nineteen galaxies from the Balcells & Peletier (1994, BP94) sample were imaged with HST/NICMOS at F160W (Peletier et al. 1999, Paper I). We have performed bulge-disk decompositions, and analyze profiles, global parameter relations and nuclear cusp slopes in a companion paper (Balcells et al. 2002, Paper III). In this Letter, we focus on the shape indices obtained from Sérsic fits to the bulge profiles. The high resolution of the HST data allows one to disentangle nuclear disks/bars and compact sources from the extended spheroid light. Modeling these components, we study Sérsic indices for the bulge profiles and compare them to those obtained from ground-based profiles. We characterize the magnitude distribution of point sources found in the galaxy centers and discuss the relevance of low-$n$ profiles for bulge formation models. Preliminary results on nuclear cusps are presented in Balcells et al. (2001).

A key ingredient of the analysis of bulge profiles, overlooked in the HST-based studies of bulges cited above, is the modeling of the extended bulge and disk light distributions when fit-
ting analytic functions to the bulge light. Here, composite profiles linking HST profiles with ground-based K-band profiles are used so that bulge-disk decompositions can be performed. We assume a Hubble constant of \( H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1} \).

2. DATA

We work with a subset of the BP94 diameter-limited sample of inclined, early-to-intermediate type disk galaxies classified as unbarred in the UGC (Nilson 1973); see Paper I and references therein. None has a Seyfert or starburst nucleus. Ground-based surface brightness profiles in the K-band for the BP94 sample, derived from ellipse fits to UKIRT/IRC3 images, are given in Peletier & Balcells (1997), while two-dimensional bulge-disk decomposition and Sérsic fits to the K-band bulge profiles are published in APB95.

The subsample studied here comprises 19 galaxies of types S0 to Sbc that were imaged with NICMOS on HST (camera 2, 19'' × 19'', 0.075 arcsec/pixel). Data reduction is described in Paper I, while details of the data analysis are given in Paper III. We derive elliptically-averaged surface brightness profiles and isophotal shapes, from 0.075'' to typically 10'', using the galphot package (Jørgensen et al. 1992). We keep the centers fixed and allow the ellipticity and position angles of the isophotes to vary. Linking the HST-F160W and ground-based K profiles is done following Paper I, with details given in Paper III.

3. BULGE-DISK FITS

The combined HST plus ground-based profiles, corrected for foreground Galactic extinction (Schlegel et al. 1998), (1 + z)^2 cosmological dimming and K-correction, were fitted with a PSF-convolved Sérsic-plus-exponential model using the code from Graham (2001) modified to use a Moffat PSF (FWHM=0.19'') [NICMOS Handbook], \( \beta=2.5 \). No internal extinction corrections were applied. A quasi-Newton algorithm (Kahaner, Moler & Nash 1989) was used to converge on the solution resulting in the smallest r.m.s. scatter, with 5 free parameters (disk \( \mu_0, h \); bulge \( \mu_e, R_e, n \)). Each fit was individually inspected. When an obvious local minimum was found, the code was run again with new initial conditions; when the apparent global minimum was found, the code was also again run with different initial conditions to provide confirmation. The final fits for every galaxy are shown in Paper III.

Such Sérsic-exponential bulge-disk fits, covering the entire radial range down to 0.075'', tend to show strong residuals, up to 0.3 mag, over the entire bulge. A typical example is shown in Figure 1a. The residual profile shows a characteristic wave pattern. This is caused by a strong central light excess, as inferred from fits excluding the central 1-2 arcsec. We then run the fitting code including either an additional central delta function point source (PS); a central exponential; a point source plus an exponential; or a central Gaussian component with free FWHM to the fitting function. In all cases each component is PSF-convolved before fitting. For each galaxy we select the simplest fit, i.e. minimum number of components, for which the residual profile falls below an amplitude of 0.1 mag/arcsec^2. Figure 1b shows the profile from Figure 1a fitted with an additional central PS, which yields an excellent fit. The total light in the inner 1-2'' can also be approximated with power laws (Balcells et al. 2001; Böker et al. 2002). The Nuker model also fits the inner few arcsec of the early-type galaxy profiles well (Byun et al. 1996). However, these approaches break down further out (e.g. Lauer et al. 1995), do not allow a bulge-disk decomposition, and are not discussed further here. Our fits extend over 2.5 decades in radius, and describe both bulge and disk.

Of the 19 galaxies, 12 yield a satisfactory fit with the addition of a single PS, 2 with the addition of a single nuclear exponential, 4 with a PS plus an exponential, and one with a pure Sérsic bulge. The frequency of PS is thus 84 ± 8%, and that of inner exponential is 32 ± 11%. Only one galaxy (NGC 5577, Sbc) does not require an unresolved source and can be fit with a simple Sérsic bulge plus exponential disk; however, the profile for this galaxy has lower S/N than the others owing to its lower surface brightness. Most galaxies with PSs yield a good fit with a Gaussian inner component instead; in those cases, the FWHM of the inner Gaussian, before PSF convolution, is generally well below the PSF FWHM, recovering the PS solution. Some galaxies with inner exponential components also admit a good fit with a marginally resolved Gaussian instead. Because these galaxies show high ellipticity and pointy isophotes in the nuclear region, we choose the PS-plus-exponential fit instead of the Gaussian inner component. Nuclear isophotes are described in Paper III.

The Sérsic index \( n_{\text{hst}} \) for the bulges ranges from 0.5 to 3.0, with a mean of \( <n> = 1.7 \pm 0.7 \). The range is significantly lower than that obtained by APB95 using ground-based data alone, which reaches \( n = 6 \): Figure 2a shows that \( n_{\text{hst}} \) is systematically lower than \( n_{\text{gb}} \), especially for galaxies with \( n_{\text{gb}} \geq 3 \). None of our bulges reaches the de Vaucouleurs \( r^{1/4} \) behaviour. It appears that fits to ground-based profiles reach Sérsic indices \( n \geq 4 \) because the light from HST-unresolved central sources, plus in some instances nuclear disks or bars, when convolved with typical ground-based seeing, link smoothly with the extended bulge profile and mimic higher-\( n \) Sérsic profiles.

Figures 2c,d plot the distribution of \( n_{\text{hst}} \) vs. the bulge-to-disk luminosity ratio (B/D) and bulge K-band absolute magnitude, respectively. B/D are derived from the best-fit parameters. Bulge absolute magnitudes are derived from the galaxy K-band magnitude given in APB95 and our computed B/D. As noted by APB95, some of the galaxy magnitudes are probably slightly underestimated when the galaxy overfills the frame.

\[ \text{Fig. 1.— (a) The combined HST+ground-based H-band surface brightness profile of NGC 5443 (Sb), with PSF-convolved Sérsic bulge and exponential disk components (solid lines). The residuals (data minus model) are shown in the lower panel. (b) The same surface brightness profile fitted with a PSF-convolved Sérsic law, an exponential disk, plus a central point source (dashed line). Residuals are shown in the lower panel.} \]
Fig. 2.— Dependence of the HST-resolved bulge Sérsic index $n_{bul}$ on global properties of the parent galaxy: (a) $n_{bul}$ vs galaxy morphological type index $T$. (b) $n_{bul}$ vs the bulge Sérsic index $n_{gb}$ obtained from ground-based data (APB95). (c) $n_{bul}$ against the bulge-to-disk ratio. (d) Bulge index $n_{bul}$ against the bulge $K$-band absolute magnitude. Filled circles: bulges, this work. Crosses: bulges from the de Jong & van der Kruit (1994) sample, as analyzed by Graham (2001) (cf. his Figure 14).

Figures 2c,d show that log($n_{bul}$) correlates with log(B/D) and with the bulge absolute $K$-band magnitude (Spearman rank-order correlation coefficients -0.52 and -0.51, significances 97.8% and 97.4%, respectively). Thus, the correlation of Sérsic index $n$ with B/D and bulge luminosity found in ground-based data (APB95; Graham 2001) remains valid when fits including central PS components are used. We compare our HST-based $n$ distributions to those obtained by Graham (2001) using the sample of spirals of de Jong (1996) (Figure 2c,d, cross symbols). The loci occupied by the two samples are similar. A trend with morphological type $T$ (Figure 2a) is apparent when our distribution is extended to later types by adding values from the Graham (2001) analysis.

4. POINT SOURCE PROPERTIES

We showed in §3 that, for 16 out of the 19 galaxies studied, adding a central PS improves the fit to the observed profile. Absolute $H$-band magnitudes for the PS are in the range $-14 > M_{H,PS} > -18$. The distribution of $M_{H,PS}$ with morphological type $T$ is quite flat (Figure 3a). $M_{H,PS}$ correlates with log($n$) and with $M_{K,Bul}$ (Spearman rank-order correlation coefficients of -0.63 and 0.77, significances 99.6% and 99.96%, respectively), see Figures 3b,c. The line in Figure 3c is an orthogonal regression to the $M_{H,PS} - M_{K,Bul}$ relation, which yields

$$L_{K,PS}/L_{K,\odot} = 10^{7.36}(L_{K,Bul}/10^{10}L_{K,\odot})^{0.50\pm0.14}.$$  \hspace{1cm} (1)

using a constant color $H-K=0.23$ for the nuclei (Persson, Frogel & Aaronson 1979).

Nuclear sources have been reported in previous studies of early-type galaxy profiles based on HST imaging. Carollo et al. (2002) detect nuclear sources in 43 of their 69 late-type galaxies, with absolute magnitudes $-10 > M_{H,PS} > -17.7$. The bright end is similar to ours. The fainter luminosities are consistent with the expected low bulge luminosity of their late type galaxies, although the lack of a bulge-disk decomposition prevents us from comparing theirs and our trends of PS luminosity with spheroid luminosity. Ravindranath et al. (2001), using twodimensional fits to HST/NICMOS F160W images of an E/S0 sample, report unresolved central components for $\sim50\%$ of their targets. Figure 3d shows their distribution of point source magnitude vs. absolute $B$-band galaxy magnitude together with our distribution of PS magnitude vs. $B$-band absolute bulge magnitude; the latter was computed using the $B_{r}$ galaxy magnitudes from the RC3 and the bulge-disk ratio derived from the $HST+$ground-based profile fits. Their point source magnitudes are slightly fainter than ours. Their fainter PS magnitudes and their lower detection rate may be consequences of their choice of the Nuker model vs. our use of the Sérsic model to fit the underlying bulge light distribution; the Nuker law is steeper than the Sérsic law near the origin, and diverges at $r=0$, whereas the Sérsic law has a finite value of $\mu(0)$. Also, using galaxy magnitudes for their sample instead of bulge magnitudes shifts their points to the right in the diagram.

5. DISCUSSION

Measuring the correct value of the Sérsic index $n$ for bulges is important for several reasons. Overestimating $n$ leads to an overestimate of the bulge $r_e$ and luminosity. Trujillo et al. (2001) show that fitting an $r^{1/2}$ profile with a $r^{1/4}$ function yields an overestimate of $r_e$ by a factor of 3-5 and of the bulge luminosity by a factor of about 2. The luminosity ratio B/D when $n$ is underestimated, eg. when exponential fits are forced onto $n>1$ Sérsic profiles (Graham 2001). Thus, small luminosity components (typically $L_{K,PS}/L_{K,Bul} \approx 10^{-2.8}$, eqn. 1) may significantly alter the derived global parameters of bulges. Test fits excluding inner profile regions suggest that, in the absence of HST imaging, the effects of central components on the bulge shape index $n$ are greatly diminished by excluding the central FWHM of the profile, as done by Stiavelli et al. (2001) for dwarf ellipticals. Point sources should present less of a problem for late-type spirals given the low Sérsic indices, low bulge luminosities and hence low PS luminosities expected from Figure 3c.

The nuclear PSs, amounting to a fraction of order $10^{-3}$ of the bulge luminosities, are easy to accommodate within either a merger origin or a secular evolution origin for bulges. The observed scaling of PS and bulge luminosities need not indicate an internal origin for the PS as nuclear gas deposition during a merger may scale with the masses of the merging objects. If bulges are evolved bars, the problem of growing a nuclear star cluster is similar to that of feeding an active galactic nucleus (Maciejewski et al. 2002).

Given the persistent description of bulges as $r^{1/4}$ spheroids in galaxy formation models, it is worth pointing out that none of the bulges follow the $r^{1/4}$ law. APB95, de Jong (1996), Graham (2001) and MacArthur et al. (2002) have shown that
late- to intermediate-type bulges have $r^{1/n}$ profiles in the range $0.5 < n < 2.0$. Our work establishes a similar range, $0.5 < n < 3.0$, for intermediate- to early-type bulges i.e. those which are still generally described with the $r^{1/4}$ model. Extrapolating from the rising envelope of the $n = M_K$ relation in Figure 2d, only bulges with $M_K \leq -26$ may reach $n = 4$. The $r^{1/4}$ law is interpreted as the consequence of violent relaxation during a clumpy collapse (van Albada 1982), and is obtained after mergers of similar-size disk galaxies (Barnes 1988). Simulations of collisionless satellite accretion onto bulge-disk galaxies further show that bulges evolve smoothly from exponential profiles to $r^{1/4}$ profiles when doubling their mass due to accretion events (ABP01). At face value then, our distribution of Sérsic shape indices $n$ (Figure 2c,d) suggests that the vast majority of bulges did not acquire their present structural properties by growing through collisionless mergers. Kinematic data might show whether, besides a low Sérsic index $n$, these bulges show other properties typical of disks (Kormendy 1993; Falcón-Barroso et al. 2002).

Have deviations from the $r^{1/4}$ law in N-body models gone undetected? Sérsic fitting is only starting to be applied in N-body studies. Hjorth & Madsen (1995) show that violent relaxation in a finite volume, combined with subsequent escape of positive-energy stars, leads to a distribution function with deviations from the $r^{1/4}$ law; from their figures, a shallow central potential might possibly fit $n < 4$ Sérsic profiles. Accretion of low-mass satellites might heat the bulge only moderately and deposite the compact satellite nucleus at the center of the remnant. This could lead to a $n \sim 1$–$2$ bulge with a central brightness spike not unlike what is observed. But very long merger times and slow growth rate for low-mass satellites are a problem for this hypothesis. Recent cosmological SPH simulations of galaxy formation (Scannapieco & Tissera 2002) find $n \approx 1$ for bulges resulting from secular evolution, while merging raises $n$ to about $n = 4$, again pointing at low-$n$ profiles being related to non-merger formation histories.

REFERENCES

Andredakis, Y. C. & Sanders, R. H. 1994, MNRAS, 267, 283
Aguerri, J. A. L., Balcells, M., Peletier, R. F. 2001, A&A, 367, 428 (ABP01)
Andredakis, Y. C., Peletier, R. F., & Balcells, M. 1995, MNRAS, 275, 874 (ABP95)
Balcells, M., Domínguez-Palmero, L., Graham, A., & Peletier, R. F. 2001, ASP Conf. Ser. 249: The Central Kiloparsec of Starbursts and AGN: The La Palma Connection, 167
Balcells, M., Graham, A. W., Domínguez-Palmero, L., & Peletier, R. F. 2002, in preparation (Paper III).
Balcells, M. & Peletier, R. F. 1994, AJ, 107, 135 (BP94)
Barnes, J. H. 1988, ApJ, 331, 699
Böker, T., Laine, S., van der Marel, R. P., Sarzi, M., Rix, H., Ho, L. C., & Shields, J. C. 2002, AJ, 123, 1389
Byun, Y.-I. et al. 1996, AJ, 111, 1889
Carollo, C. M., Stiavelli, M., Mack, J. 1998, AJ, 116, 68
Carollo, C. M., Stiavelli, M., Seigar, M., de Zeeuw, P. T., & Dejonghe, H. 2002, AJ, 123, 159
Combes, F., Debbasch, F., Friedli, D., & Pfenniger, D. 1990, A&A, 233, 82
Courteau, S., de Jong, R. S., & Broeils, A. H. 1996, ApJ, 457, L73
de Jong, R. S. 1996, A&AS, 118, 557
Falcón-Barroso, J., Balcells, M., Peletier, R. F. & Vazdekis, A. 2002, A&A, submitted
Graham, A. W. 2001, AJ, 121, 820
Hjorth, J. & Madsen, J. 1995, ApJ, 445, 55
Jørgensen, I., Franx, M. & Kjærgaard, P. 1992, A&AS, 95, 489
Kahaner, D., Moler, C., & Nash, S. 1989, in Numerical Methods and Software, Englewood Cliffs: Prentice Hall
Kauffmann, G., Charlot, S., & White, S. D. M. 1996, MNRAS, 283, L117
Khosroshahi, H. G., Wadadekar, Y., & Kemball, A. 2000, ApJ, 533, 162
Kormendy, J. F., in IAU Symp. 153, Galactic Bulges, ed. H. J. Habing & H. B. Dejonghe (Dordrecht:Kluwer), 209
Lauer, T. R. et al. 1995, AJ, 110, 2622
MacArthur, L. A., Courteau, S., Holtzman, J. A. 2002, ApJ, accepted
Maciejewski, W., Teuben, P. J., Sparke, L. S., & Stone, J. M. 2002, MNRAS, 329, 502
Möllenhoff, C. & Heidt, J. 2001, A&A, 368, 16
Nilson, P. 1973, Uppsala Astron. Obs. Ann., 6 (UGC)
Peletier, R. F. & Balcells, M. 1997, New Astronomy, 1(4), 349
Peletier, R. F., Balcells, M., Davies, R. L., Andredakis, Y., Vazdekis, A., Burkert, A., & Prada, F. 1999, MNRAS, 310, 703 (Paper I)
Persson, S. E., Frogel, J. A., & Aaronson, M. 1979, ApJS, 39, 61
Pfenniger, D. & Norman, C. 1990, ApJ, 363, 391
Phillips, A. C., Illingworth, G. D., MacKenty, J. W., & Franx, M. 1996, AJ, 111, 1566
Pizzella, A., Corsini, E. M., Morelli, L., Sarzi, M., Scarlata, C., Stiavelli, M. & Bertola, F. 2002, ApJ, 573, 131
Ravindranath, S., Ho, L. C., Peng, C. Y., Filippenko, A. V., & Sargent, W. L. W. 2001, AJ, 122, 653
Rest, A., van den Bosch, F. C., Jaffe, W., Tran, H., Tsvedanov, Z., Ford, H. C., Davies, J., & Schafer, J. 2001, AJ, 121, 2431
Scanapieco, C., Tissera, P. 2002, MNRAS, accepted (astro-ph/0208538)
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Seigar, M., Carollo, C. M., Stiavelli, M., de Zeeuw, P. T., & Dejonghe, H. 2002, AJ, 123, 184
Seigar, M. S. & James, P. A. 1998, MNRAS, 299, 672
Simard, L. et al. 2002, ApJS, 142, 1
Stiavelli, M., Miller, B. W., Ferguson, H. C., Mack, J., Whitmore, B. C., & Lotz, J. M. 2001, AJ, 121, 1385
Sérsic, J. L. 1968, Atlas de Galaxias Australes (Córdoba:Observatorio Astronómico)
Trujillo, I., Graham, A. W., & Caon, N. 2001, MNRAS, 326, 869
van Albada, T. S. 1982, MNRAS, 201, 939