The Central kpc of Galaxy Bulges

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Abstract. We study the innermost regions of bulges with surface brightness data derived from combined HST/NICMOS and ground-based NIR profiles. Bulge profiles to 1-2 kpc may be fit with Sersic laws, and show a trend with bulge-to-disk ratio: low-B/D bulges are roughly exponential, whereas higher-B/D bulges show increasing Sersic shape index $n$, indicating higher peak central densities and more extended brightness tails. $N$-body models of accretion of satellites onto disk-bulge-halo galaxies show that satellite accretion contributes to the increase of the shape index $n$ as the bulge grows by accretion. The $N$-body results demonstrate that exponential profiles are fragile to merging, hence bulges with exponential surface brightness profiles cannot have experienced significant growth by accretion of dense satellites.

1. Introduction

Bulges are the dominant mass and light component of the central kpc in early- and intermediate-type disk galaxies, thus it is appropriate to address their formation and evolution at this conference. Bulges are often assimilated to small ellipticals residing in the centers of spirals, and indeed the similarities include structure, colors, populations (Wyse, Gilmore, & Franx 1997), age (Peletier et al. 1999) and position in the Fundamental Plane (Falcon-Barroso, Peletier, & Balcells 2001). However, the intimate scaling of disk and bulge luminosity and structural sizes along the Hubble sequence (de Jong 1996, Courteau & de Jong 1997, Graham 2001) and the similarity of their colors (Peletier & Balcells 1997) indicate that bulge and disk have known about each other during their formation and growth, and that understanding a galaxy amounts to more than understanding its components.

An increased attention to bulges during the nineties has allowed us to improve on the picture that bulges are described by the $r^{1/4}$ surface brightness law, that they are isotropic oblate rotators (Kormendy & Illingworth 1983) and that their populations are of high metallicity (Rich 1988). As first noted for the Milky Way bulge by Kent, Dame, & Fazio (1991), small bulges have exponential surface brightness profiles (Andredakis & Sanders 1992, Andredakis, Peletier, & Balcells 1995, de Jong 1996). Box- and peanut-shaped bulges have cylindrical rotation (Shaw, Wilkinson, & Carter 1993) and show the kinematic signature of barred dynamics (Kuijken & Merrifield 1995; Bureau & Freeman 1999). The stellar populations of bulges have below-Solar metallicities (Balcells & Peletier 1994; Sadler, Rich, & Terndrup 1996). Recently, a strong correlation has been
found between the mass of central black holes and the velocity dispersion of the bulges they reside in (Magorrian et al. 1998; Merrit & Ferrarese 2001).

On the theoretical side, $N$-body models have shown that vertical buckling instabilities in bars may form a peanut-shaped bulge-type object at the center of disk galaxies (Combes & Sanders 1982; Hassan, Pfenniger & Norman 1993). Bulges may therefore be by-products of disk secular evolution. That bulges do not always precede disk formation is evidenced by the fact that bulge-less galaxies do exist.

Their high central densities suggests that bulge formation involves violent, efficient starbursts, while their z-extent suggests violent dynamical processes involving disk instabilities or merging.

These findings have added new ingredients to the basic questions on bulges: how old are bulges; do bulges form before/after/simultaneously with their disks; do bulges grow and does the galaxy evolve along the Hubble sequence; is there a dichotomy, such that old bulges are old collapse/merger products and small bulges are young products of disk instabilities; is bulge formation and growth connected to black hole formation and growth.

To some degree any study of bulges addresses what we understand by bulges. The term 'bulge' refers to the swelling at the center of the spiral disk, hence to the extended structure. But because this swelling can only be observed in the most edge-on cases, in practice bulges are taken to be the central brightness increase above the inward extrapolation of the exponential disk profile. Because the disk may contain structural components embedded in the bulge, eg. bars, these two definitions need not describe the same structures.

In this paper I review the systematics of bulge surface brightness profiles, as derived on a sample of early- to intermediate-type inclined galaxies, and describe the results of $N$-body merger studies of the effects of satellite accretion on the surface brightness profiles. I then present our work on combined HST+ground based NIR surface brightness profiles, which map bulges from $\sim20$ pc to a few kpc.
2. The Sample

We work on a diameter limited, statistically complete sample of 30 unbarred, inclined ($i > 50^\circ$) galaxies from the UGC (Nilson 1973), of types from S0 to Sbc. Published papers on this sample address optical colors, NIR surface brightness profiles, bulge-disk decomposition, disk-bulge colors, ages, and Fundamental Plane (Balcells & Peletier 1994; Peletier & Balcells 1996; Peletier & Balcells 1997; Peletier et al. 1999; Falcón-Barroso, Peletier, & Balcells 2001; Balcells et al. 2001). All of our ground-based imaging data is made freely available in an electronic atlas (Peletier & Balcells 1997).

3. Dichotomy vs continuum of shapes

The departure of bulges from the $r^{1/4}$ surface brightness law has been approached in different ways by different authors. The most convenient method is to use Sersic’s (1968) law,

$$I(r) = I_e \cdot \exp \left\{ -b_n \cdot \left[ \left( \frac{r}{r_e} \right)^{1/n} - 1 \right] \right\},$$

with $b_n \approx 1.9992 \cdot n - 0.3271$ (Caon, Capaccioli, & d’Onofrio 1993). We refer to $n$ as the shape index or concentration index. Exponential profiles are obtained setting $n = 1$, and $n = 4$ gives the $r^{1/4}$ law. One approach is to choose the best fitting $n$ from the set $n = 1, 2, 4$ (de Jong 1996; Graham & Prieto 1999). A more restricted approach is to simply classify objects into two groups, the "exponential bulges" ($n = 1$) and the "$r^{1/4}$ bulges" ($n = 4$; Carollo 1999). Such approaches may be over restrictive as, in fact, $n$ seems to be continuously distributed (Andredakis et al. 1995; Graham 2001). The latter two papers demonstrate that $n$ strongly correlates with B/D and with the total luminosity of the bulge, in the sense that late-type galaxies are constrained to $n < 1$ while early-type spirals show $n$ reaching up to $n \sim 5$ (Fig. 1). This result holds for both blue and NIR passbands and is irrespective of whether the bulge-disk decomposition is done on the 1D surface brightness profile (Graham 2001) or in a model-independent fashion using ellipticity signatures of the bulge (Andredakis et al. 1995). Graham (2001) shows that choosing the wrong $n$ leads to distortions on other parameters such as the disk effective radius and the B/D.

The trend of $n$ vs luminosity in bulges follows a similar trend found by various authors for ellipticals (eg. Caon et al. 1993, Trujillo et al. 2001) and spans a range of 8 magnitudes.

What clues does that trend contain about the formation of ellipticals and bulges? Andredakis (1998) studied the effects of the disk potential on the surface brightness profile of the bulge, using $N$-body simulations of the adiabatic growth of a disk potential on a pre-existing $r^{1/4}$ bulge. He shows that the disk potential drives the $r^{1/4}$ profile toward lower $n$. However, the effect saturates around $n = 2$, demonstrating that the disk potential alone cannot turn $r^{1/4}$ spheroids into exponentials.
4. Growth of bulges: testing the accretion hypothesis

The continuity of the trend along the bulges and ellipticals suggests a process that operates on all spheroids independent of the presence of a massive disk. Aguerri, Balcells & Peletier (2001) have used N-body merger simulations to investigate the effects of the accretion of satellites on the surface brightness profiles of bulges. They study the scenario in which initially small, exponential bulges grow by accretion of satellites. The aim is to see whether bulge growth is accompanied by an increase of the shape index $n$. This scenario fits in with the fact that low-luminosity bulges are those with exponential profiles.

Simulations use the Kuijken & Dubinski (1995) disk-bulge-halo galaxy model as the primary, and either a King or a Hernquist (1990) sphere for the satellite. Evolution is computed with Heller’s treecode (Heller & Schlosman 1994), using $N=110,000$ particles. Simulation details are given in the reference above. Experiments explore a range of satellite masses, prograde and retrograde merger orbits and two different satellite models. Secondary mergers, as well as one low-density satellite case, are also studied. In all cases, the system is allowed to merge and relax, after which the face-on surface density profile is extracted and fitted with exponential plus Sersic laws. The fit procedure is similar to that done on the profiles of real galaxies, and produces best-fit parameters $R_e$, B/D, disk scale length $h$ and central surface brightness $\mu_0$, in addition to the bulge shape index $n$. This allows one to draw growth vectors in the $n$-B/D plane. Examples of merger remnant surface density profiles are shown in Figure 2a.

When an accreted satellite reaches the bulge, $n$ rapidly increases as B/D grows. Figure 2b shows growth vectors for bulges in the merger simulations, together with the distribution of bulges in Andredakis et al. (1995). Roughly a 25% in B/D is associated to an increase $\Delta(n) = 1$, and a satellite as massive as the bulge results in an $r^{1/4}$ final bulge. To first order the effect is cumulative, ie a second accretion causes the same increment in $\log(B/D)$ and $n$ as the first (see inset to Fig. 2b). The evolution drawn by the mergers in broad terms reproduces...
the distribution of observed bulges, although it is steeper in the simulations. This may be due in part to the fact that both the initial bulges and the satellites are more massive in the simulations than in many of the observed galaxies, as well as to the dense nature of the satellites used in this set of simulations.

The increase of $n$ in the models is due to both mass deposition and to heating of the bulge mass distribution. High-$n$ Sersic profiles have both high central peaks and extended tails; in the models, it is the tails which drive the increase of $n$, as the models lack central resolution. We note that mass pile-up at the center includes disk material drawn in by transient bar distortions during the merger. The standard bulge-disk decomposition, which fits the disk with a simple exponential, assigns some of this central disk material to the bulge. This may contribute to the color similarity between the bulge and the inner disk (Peletier & Balcells 1996).

The bulge only evolves if and when the satellite reaches the bulge before disrupting. Low density satellites deposit the mass in the halo and the disk, and the bulge remains unaffected. It will be useful to investigate satellites with a range of density profiles, which may show behaviours intermediate between the high-density cases which fully merge with the bulge, and the low-density cases which leave the bulge unaffected.

As expected, the accretion of the dense satellite heats up the disk (eg. Quinn, Hernquist, & Fullagar 1993). Aguerri et al. (2001) show that the remnant disk presents a significant increase in scale length $h_D$ in addition to an increase of scale height. Such disks resemble thick disks observed in early-type disk galaxies (eg. de Grijs & Peletier 1997), hence satellite accretion may explain both the high-$n$ bulges and the thick disks of early-type spirals. A match to real galaxies presupposes the formation of a new thin disk out of the gas left over in the merger (Kauffmann, Guiderdoni, & White 1994), implying that our scenario is one of bulge-before-the-disk, despite the existence of a disk before the merger.

Further simulations, with higher central resolution and with a range of satellite densities, should provide additional tests on this hypothesis.

5. Bulge structure down to 20 pc

Elsewhere in this volume, Balcells et al. (2001) present NIR ($\sim H$)-band surface brightness profiles obtained by matching HST/NICMOS F160W profiles to ground-based $K$-band data, for a fraction of the Balcells & Peletier (1994) sample. Adding the interesting 20 pc – 200 pc radial range, the profile fits give systematic higher $n$, but still show a dependency of $n$ with B/D. The profiles in the inner arcsec appear as clean power laws reminiscent of those found by Lauer et al. (1995) for ellipticals.

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