Carnegie Observatories Astrophysics Series, Vol. 1:
Coevolution of Black Holes and Galaxies, 2004
ed. L. C. Ho (Cambridge: Cambridge Univ. Press)

The Inner Properties of Late-type Galaxies

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Abstract

I review some recent results on the inner properties of disk galaxies, and highlight some issues that require either observational or theoretical clarification and that are important for constructing a consistent picture of the formation of the local disk galaxy population.

1.1 Disk Galaxies: Recipe Still Missing

We have not yet achieved a self-consistent theoretical scenario for the formation of the local disk galaxy population, a population which, in crude terms, is a mix of "bulged" and "bulgeless" disks. The origin of the bulges is vigorously debated. In a recent paper in the proceedings of the 1998 workshop on "The Formation of Bulges" (Carollo, Ferguson, & Wyse 1999), Renzini (1999) voices with emphasis the long-standing belief that bulges are nothing more or less than small elliptical galaxies. Basing his argument on the similarity between the magnesium line strength Mg_2 versus absolute r magnitude M_r (and magnesium line strength Mg_2 and velocity dispersion σ; Jablonka, Martin, & Arimoto 1996) relations for bulges and ellipticals, he writes: "*...The close similarity of the $Mg_2 - M_r$ relations argues for spiral bulges and ellipticals sharing a similar star formation history and chemical enrichment. One may argue that origin and evolution have been very different, but differences in age distribution are precisely compensated by differences in the metallicity distributions. This may be difficult to disprove, and I tend to reject this alternative on aesthetic grounds. It requires an unattractive cosmic conspiracy, and I would rather leave to others the burden of defending such a scenario. In conclusion, it appears legitimate to look at bulges as ellipticals that happen to have a prominent disk around them, or to ellipticals as bulges that for some reason have missed the opportunity to acquire or maintain a prominent disk.*"

And yet, there is plenty of evidence from observations and numerical experiments that bulges of spiral galaxies may differ significantly from elliptical galaxies. In a pioneering paper, Kormendy (1993; see also Kormendy, Bender, & Bower 2002) reports, for some Sb bulges, V/σ values that are above the oblate line describing the isotropic spheroids in the V/σ-ϵ diagram (with V the maximum velocity, σ the mean velocity dispersion, and ϵ the mean ellipticity of the spheroid; Binney & Tremaine 1987), and makes the point that at least some of the dense structures that are seen inside the disks may actually themselves be disklike systems ("pseudo-bulges"). In numerical simulations, three-dimensional stellar structures result from secular evolution processes that are driven by dynamical instabilities inside the preexisting disks. The fire-hose (or buckling) instability that is seen in simulations of stellar disks can scatter the stars originally in a stellar bar above the plane of the disk, into what resembles a bulgelike structure (Raha et al. 1991). A stellar bar can also drive a high inflow rate of gas toward the center of the disk (Shlosman, Frank, & Begelman 1989); if a mass concentration of the order of $\sim 1\%$ of the total mass is accumulated in the center, this can disrupt the regular orbits supporting the bar and again scatter the stellar orbits above the plane of the disk (Pfenniger & Norman 1990; Norman, Sellwood, & Hasan 1996).

The disks of spiral galaxies also elude us. On large galactic scales, they are a rather homogeneous family, as indicated, for example, by their light profiles, which appear to be exponential over several disk scale lengths (de Jong 1995), the rather common asymptotically flat rotation curves (Persic & Salucci 1995), and the Tully-Fisher relation, which holds over a broad range of surface brightness and mass (Strauss & Willick 1995). On smaller scales, however, where they physically overlap with the bulges (and the rest of the inner structure), disks are not well understood, either observationally or theoretically. Within hierarchical formation schemes, the standard recipe to explain the formation of disks contains three key elements: (1) the angular momentum originates from cosmological torques (Hoyle 1953), (2) the gas and dark matter within virialized systems have initial angular momentum distributions that are identical (Fall & Efstathiou 1980), and (3) the gas conserves its specific angular momentum when cooling (Mestel 1963). These rules are routinely assumed in the (semi-)analytical descriptions of disk galaxies. In contrast, the highest resolution cosmological simulations that include both baryons and cold dark matter (CDM) find significant angular momentum loss for the baryons, especially in the central few kpcs of galaxies (Steinmetz & Navarro 1999). Furthermore, even when disks are assumed to form smoothly and conserving their angular momentum, the resulting disks are more centrally concentrated than single-exponential structures (Bullock et al. 2001; van den Bosch 2001; van den Bosch et al. 2002). Disks with high central densities are seen in the highest-resolution CDM simulations, in which the resulting galaxies have realistic sizes, but a region with low angular momentum and high density is always present at the center (e.g., Governato et al. 2004). It is still a matter of debate whether this is a feature of the structure formation model or is indicative of the lack of a proper treatment of physics (e.g. the effect of supernovae feedback; Springel & Hernquist 2002). Although the CDM simulations still have room for improvement, they could well be correct in their prediction that the central parts of disks might really have quite low angular momentum and high concentration as a result of formation. Although warm dark matter alleviates the angular momentum "catastrophe" (i.e., the loss of angular momentum by the baryons), the angular momentum distributions of warm dark matter halos is identical to that of CDM halos (Knebe, Islam, & Silk 2001; Bullock, Kravtsov, & Colin 2002). Therefore, these halos also predict an excess of low-angular momentum material.

Clearly the central regions of disk galaxies hold important clues to understanding fundamental issues of galaxy formation. Shaping a consistent theory of bulge and disk assembly requires a better understanding of nearby disk galaxies on the nuclear and circumnuclear scales. High-resolution studies of real and simulated disk galaxies are still in their infancy, but have made their first steps in the last few years. Recent reviews on disk galaxies and their subcomponents are presented by Wyse, Gilmore, & Franx (1997) and Carollo et al. (1999). In this review I focus on some recent developments on the central regions of nearby disk galaxies, and discuss some of the related important issues that require future attention. In order to remain faithful to the original studies, and following customary classification schemes, I will often discuss the results maintaining a distinction among systems of early, intermediate, and late types; however, it is this very distinction that I challenge in my concluding remarks.

1.2 First Fact: Complexity is the Rule

All recent high-resolution studies consistently report a large complexity in the inner regions of at least half of the local disk galaxy population of all Hubble types. On scales smaller that 1 kpc, more than half of the galaxies host inner bars (within bars), dust or stellar or gaseous disks, spiral-like dust lanes, star-forming rings, spiral arms, a central cluster (§ 1.5), or simply irregular central emission. (e.g., Carollo et al. 1997c; Carollo, Stiavelli, & Mack 1998; Martini & Pogge 1999; Laine et al. 2002; Böker, Stanek, & van der Marel 2003).

Nuclear bars have received particular attention, as they are claimed to play an important role in feeding gas into the centers of galaxies (Shlosman et al. 1989), potentially building central nuclei and bulges, and fueling nuclear activity. Intimate links between bars and central starbursts, in particular circumnuclear star-forming rings, are supported by observations (Knapen, Pérez-Ramírez, & Laine 2002). Other studies point out, however, that, on the nuclear scales, stellar rings and inner disks inside large-scale bars of moderately inclined galaxies could be mistaken for secondary bars or even coexist with them, producing erroneous statistics for the occurrence of nuclear bars (Erwin & Sparke 1999). Still, *bona fide* secondary inner bars, typically about 250 pc–1 kpc in size ($\sim$12% the size of their primary bars) appear to be present in as many as 40% of all barred S0–Sa galaxies (Erwin & Sparke 1999). Larger samples of early-type galaxies confirm a high frequency of detection of bars-within-bars (Rest et al. 2001). This high frequency is interpreted to indicate that secondary nuclear bars are relatively long-lived structures. The presence or absence of secondary bars appears to have no significant effect on nuclear activity (as previously reported by, e.g., Regan & Mulchaey 1999). In contrast, nuclear spirals, dusty or star-forming nuclear rings, and off-plane dust are reported to be very often accompanied by LINER or Seyfert nuclei (Erwin & Sparke 1999; Martini & Pogge 1999).

Circumnuclear starburst rings have also been thoroughly investigated (e.g., Maoz et al. 1996, 2001). These rings appear to be a common mode of starbursts in relatively early-type disk galaxies, and are thought to be associated with inner-Linblad resonances. They contain super star clusters with total luminosities as high as $M_V \approx -15$ mag ($L_V \approx 1.3 \times 10^8 L_{V,\odot}$), radii of the order of a few parsecs, and masses in excess of $10^4 M_\odot$. These clusters are very similar to the super star clusters formed in merging systems (e.g., Whitmore et al. 1999; Hunter et al. 2000): they are bound systems, believed to evolve into stellar structures similar to globular clusters. The starburst rings are thought to be likely associated with bar-driven inflow. Schinnerer et al. (2002) report in the double-barred galaxy NGC 4303, which also hosts a circumnuclear star-forming ring (Colina & Arribas 1999), an extremely good agreement between the observed overall gas geometry and dynamical models for the gas flow in barred galaxies (Englmaier & Shlosman 2000). Observational evidence seems thus to be accumulating in support of the theoretical prediction that disk instabilities on large scales are major drivers of evolution on circumnuclear (and nuclear) galactic scales. Similar to nuclear bars, circumnuclear star-forming rings are found to coexist with AGNs but are not associated one-to-one with AGN activity.

1.3 News on Bulges

It has been known for some time that many bulges have a radial light profile that is not an elliptical-like $r^{1/4}$ law (Andredakis & Sanders 1994; de Jong 1995; Courteau, de Jong, & Broeils 1996); instead, they are reasonably well described by an exponential light profile. Incidentally, the bulge of our own Milky Way also has an exponential light profile (Binney, Gerhard, & Spergel 1997). Recent high-resolution investigations using data from the *Hubble Space Telecope (HST)* have strengthened the evidence for exponential light profiles down to the smallest scales at the end of the spheroids luminosity sequence (Carollo et al. 1998, 2001; Carollo 1999). Several studies have used the generalized surface density profile $I(r) \propto \exp[-(r/r_o)^{(1/n)}]$ introduced by Sérsic (1968) to model the bulge light (Andredakis, Peletier, & Balcells 1995; Graham 2001; MacArthur, Courteau, & Holtzman 2003). These studies report shape-parameter values for bulges of late-type spirals ranging between n = 0.1 and 2. Some of the Sérsic analyses attribute a significant meaning to the derived precise values of n (Graham 2001; Balcells et al. 2003). Tests based on simulated data, however, show a large dependence of the derived parameters on, for example, the input parameters; indeed, MacArthur et al. (2003) stress that, on average, the underlying surface density profile for the late-type bulges is adequately described by an exponential distribution. The same studies show the existence of a coupling between bulges and disks that is manifested by an almost-constant scale lengths ratio $h_{\rm bulge}/h_{\rm disk} \approx 0.1$ for late-type spirals, and a similar scaling relation even for earlier-type systems. This is interpreted to indicate a similar origin for bulges of all sizes in hosts of any Hubble type.

For more massive, early-type bulges, ground-based studies using the Sérsic law to describe their light distribution have found values of n close to, or even in excess of the elliptical-like de Vaucouleur's (1948) value of $n = 4$ (Graham 2001). However, the analysis of high-resolution *HST* images for a sample of early-type bulges provides values of the Sérsic shape index n not in excess of ~ 3 (Balcells et al. 2003). The difference in the estimates for n is due to the contribution of photometrically distinct central point sources, which at ground-based resolution are confused for bulge light (see §1.5). Balcells et al. interpret the $n < 3$ Sérsic shape indices in the massive bulges as an indication that even these systems, like the smaller exponential-type bulges, are not the outcome of violent relaxation during collisionless accretion of matter. Both in the ground-based and *HST* analyses, a trend remains between the bulge Sérsic shape parameter n and the bulge luminosity and half-light radius; the trend is in the direction of brighter, bigger bulges having larger n values (Graham et al. 2001; Balcells et al. 2003).

Detailed studies of the integrated stellar populations of bulges of all Hubble types have also been pushed forward by the availability of high-resolution multi-color images from the *HST* (Peletier et al. 1999; Carollo et al. 2001). The independent analyses agree on the basic result that (1) massive early-type bulges have very red colors, unambiguously indicating old ages ($\gtrsim 8$ Gyr) for the average stellar populations of these systems, and (2) the smaller, later-type (almost) exponential bulges have on average significantly bluer colors.

Kinematically, the Sb pseudo-bulges studied by Kormendy (1993) represent the extreme case of a general behavior shown by bulges of any Hubble type and mass: these all appear to have kinematic properties that are closer to disklike structures rather than to elliptical galaxies. Indeed, based on the comparison between minor axis radial velocity dispersions of disks and bulges, Falcón-Barroso et al. (2003) report that even the early-type, massive bulges are actually thickened disks.

The following important considerations on bulges that emerge from the above analyses. (1) The earlier-type bulges form a continuum with the late-type bulges in terms of the shapes of the surface brightness profiles. The smallest bulges are exponential structures, and the largest appear to be intermediate cases between the exponential and the elliptical-galaxy ones. (2) Bulges of spirals are coupled to their host disks in a similar way along the Hubble sequence (with a possible weak trend toward marginally higher $h_{\rm bulge}/h_{\rm disk}$ ratios for early-type bulges). (3) There is a spread in average stellar metallicity and ages amongst bulges, but also a clear trend toward smaller bulges being less enriched and younger stellar structures than the more massive, earlier-type bulges. (4) Bulges of any size show some kinematic features that are typical of disks.

1.4 News on Disks

Recent surveys with the *HST* that have focused on the late-type, allegedly bulgeless Scd–Sm disks, find that only $\sim$30% of these systems have light profiles consistent with being single-exponential structures (Böker et al. 2003). The remaining disks are not well fitted by a single exponential; in particular, the surface brightness in the central few kiloparsecs exceeds the inward extrapolation of the outer exponential disk. The surface brightness profiles of many of these late-type disks are often equally well described either by the sum of two exponential components, or by a single Sérsic profile over the entire radial range with shape parameter n up to a value of 2.5. In the earlier-type systems, a second central exponential component in addition to the outer exponential disk is typically interpreted as a bulge component. Böker et al. (2003) suggest that the frequent detection of such central exponential "excesses" also in systems that, according to the classical classification scheme, should host no bulge component, together with the fact that a single Sérsic profile is often a good alternative to the sum of two exponentials, may indicate that in fact these excesses are not bulges, but rather denser regions of the disks themselves.

A key issue in the context of understanding the nature of the central regions of disk galaxies is one of definitions (see Carollo et al. 1999). Böker et al. distinguish between what they call "the modern theorist" view, assumed to be the correct one, which asserts that a bulge is a kinematically hot component with an extended three-dimensional structure, and the "observers" view, which, in photometric studies, relies on the assumption that disks are exponential structures and that bulges are identifiable as additional light (mass) contributions in the central regions. All the photometric analyses of the local (and distant; see, e.g., Shade et al. 1996) disk galaxy population that are aimed at studying bulge properties indeed assume a constant scale length exponential profile for the disk, and attribute to a bulge any central concentration of light in excess of the inward extrapolation of the outer, constant scale length disk (e.g., Andredakis & Sanders 1994; Andredakis et al. 1995; de Jong 1995; Courteau et al. 1996; Carollo et al. 1998; Balcells et al. 2003; MacArthur et al. 2003). Böker et al. (2003) mention a lack of theoretical support for the disks being exponential, and point out that the assumption that disks remain exponential all the way into the center may not be correct, i.e., that the operational definition of bulges adopted in photometric studies may lead to attributing to a bulge what actually belongs to the disk. It is certainly not an easy task to disentangle into distinct subcomponents the centers of galaxies, where all of these subcomponents are expected to reach their largest densities.

1.5 A Zoom on the Centers: Point Sources and Distinct Nuclei

Photometrically distinct compact nuclei have been known for a while to reside in the centers of bulgeless, weakly active or inactive late-type disks (e.g., Kormendy & McClure 1993; Matthews & Gallagher 1997). Extensive surveys with the *HST* show, however, that distinct pointlike or compact nuclei are the rule rather than the exception in the centers of all sorts of disk galaxies.

An optical (V, WFPC2) and near-infrared (H, J, NICMOS) survey of ~ 100 intermediate-type, Sb-Sc spirals shows that $\sim 70\%$ of these systems host distinct nuclei with visual absolute magnitudes $-8 \gtrsim M_V \gtrsim -16$, comparable at the bright end with young super star clusters in starbursting galaxies (Carollo et al. 1997c, 1998, 2002). Some of these nuclei appear pointlike in the *HST* images. However, many are marginally resolved with half-light radii $\sim 0\farcs1$–$0\farcs2$, corresponding to linear scales of a few to up to $\sim$20 pc. These nuclei cover a large range of colors in the range $-0.5\,\mathrm{mag} \lesssim V-H \lesssim 3\,\mathrm{mag}$. Statistically, the distribution of $V-H$ colors is broader for the nuclei than for the surrounding galactic structure; this suggests that star formation, AGN activity, dust reddening, or a combination of these is generally present in the nuclei embedded in intermediate-type hosts. Most of the nuclei, at *HST* resolution, are located at the galaxy centers and appear to be round, star-cluster-like, structures. However, in some cases the nuclei are offset from the isophotal/dynamical centers of the host galaxies or show some degree of elongation (as it is the case for, e.g., the nucleus of M33; Kormendy & McClure 1993; Lauer et al. 1998; Matthews et al. 1999). Both the displacement, which is typically of a few tens of parsecs, and the elongation appear to be uncorrelated with either the luminosity and color of the nucleus, or with the galaxy type. Searches for trends with other galactic subcomponents reveal no clear relationship between the distinct nuclei and nuclear (or even larger-scale) bars: bars are neither ubiquitous nor unusual in nucleated intermediate-type spirals. Some of the nuclei are embedded in exponential-type bulges; actually, every such bulge in this sample hosts a distinct nucleus in its isophotal center or slightly offset from it. These nuclei have low to moderate luminosities, $-8\,\mathrm{mag} \gtrsim M_V \gtrsim -12$ mag. Selection effects may be present. Brighter nuclei are typically embedded in very complex circumnuclear structures that do not allow for the derivation of reliable bulge parameters. Moreover, exponential-type bulges lying under substantial circumnuclear structure but hosting no central nucleus would also, for similar reasons, drop from the sample. The nuclei that have been identified inside the exponential-type bulges have colors compatible with those arising from stellar populations. Under the assumption of no dust reddening, average stellar ages of $\sim$1 Gyr are inferred for these relatively faint central star clusters; these ages, in turn, imply masses of about 10^6 to 10^8 $M_\odot$.

Studies of large samples of Scd and later-type disks also find compact, distinct nuclei, identified as "star clusters," in about 75% of the population (Böker et al. 2002). Their distribution of absolute luminosities has a FWHM of about 4 mag and a median value of $M_I = -11.5$ mag. These luminosities, as well as the sizes of these star clusters, are comparable to those of the nuclei embedded in the earlier-type galaxies. For 10 nuclei in the Böker et al. (2002) sample, Walcher et al. (2004) report spectroscopic estimates for the stellar ages that are smaller than about 1 Gyr, and masses of the nuclei estimated from stellar velocity dispersions in the range $10^6 - 10^8$ $M_\odot$. These masses are similar to the photometry-based mass estimates derived for the clusters embedded in the exponential-type bulges, and are one order of magnitude higher than expected from stellar synthesis models. These authors interpret this discrepancy as due to old(er) stellar generations contributing to the total mass of the nuclei. They conclude that the nuclei of late-type disks are grown in multiple star formation events, and suggest that this mechanism may contribute to the formation of Kormendy's pseudo-bulges.

At the other extreme of the Hubble sequence, the large majority of the early-type spiral galaxies that host massive bulges also require a central component, in addition to the bulge and the disk, to reproduce the observed light profiles (Balcells et al. 2003). In most cases, this additional component appears to be a point source at the resolution of NICMOS on the *HST*. Balcells et al. point out that in ground-based data these additional light contributions cannot be disentangled from the bulge light and may produce overestimates of the derived Sérsic n parameter (see §1.3).

1.6 Future Challenges

1.6.1 Disks

The claim that there is no strong theoretical support for the disks to be exponential (Böker et al. 2003) is partly substantiated by the fact that theories are often tuned so as to reproduce an exponential light profile. While reproducing exponential light profiles is considered to be a test for viable models of disk formation (e.g., Dalcanton, Spergel, & Summers 1997; Silk 2001), it is certainly true that most of the current disk models and simulations do predict large mass fractions with low-angular momentum material that is in excess of the extrapolation of the outer exponential density distribution to the center (see §1.1 and references therein). However, the real problem is to understand whether this excess low-angular momentum material does remain in the disk, or rather forms a three-dimensional bulge.

Furthermore, it is also possible that, rather than being born denser than exponential, the disks may become so during the subsequent galactic evolution. Indeed many processes can occur during the Hubble time that can transform exponential disks into the more complex structures that are observed in late-type disks. In this context, it is worth stressing that a third of the late-type disks remais well described by the simple single-exponential form, showing that this channel of disk formation is indeed accessible to real galaxies.

An obvious example of change in central concentration in disks is the one induced by the formation and subsequent buckling of a stellar bar. To study at unprecedented resolution the effects of secular evolution processes on the central regions of disks, we are conducting state-of-the-art N-body and N-body+SPH numerical simulations of disk galaxies (details will be published in Debattista et al. 2004 and Mayer et al. 2004). The first N-body experiments that I briefly discuss here (from Debattista et al. 2004) consist of live disk components inside frozen halos described either by a spherical logarithmic potential with a central core or a cuspy Hernquist (1990) potential. The initially axisymmetric disks are modeled assuming an exponential profile with a Gaussian thickening; the disks are represented by $(4-7.5)\times 10^6$ equal-mass particles. The spatial resolution that is achieved in the central regions is $\sim$50 pc. The simulations are run on a 3-D cylindrical polar-grid code (described in Sellwood & Valluri 1997). In certain areas of parameter space, the axisymmetric systems are found to be unstable and form bars. Systems in which bars fail to form have only modest heating, indicating that our results are not driven by noise. Every 20 time steps of the disk evolution, we measure the disk velocity dispersions and streaming velocities in annuli, the amplitude of the bar from the $m = 2$ Fourier moment, and the amplitude of the buckling from the $m = 2$ Fourier moment of the vertical displacement of particles. We use these quantities

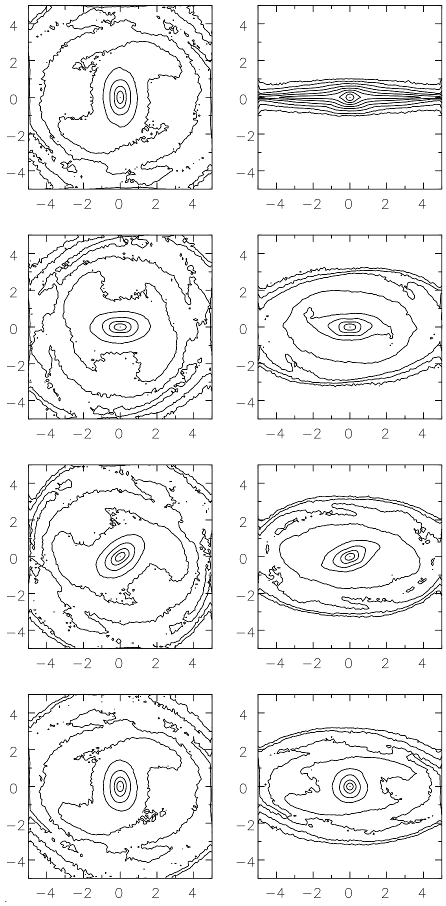

Fig. 1.1. Contour plots for a live-disk/frozen-halo simulation after the development and buckling of a stellar bar. The halo has a Hernquist (1990) profile; the disk initially has a single-exponential profile. Shown are the face-on and edge-on views of the system (upper panels, left and right, respectively), and two different views with disk inclination angles of 30° (left) and 60° (right), respectively. Different panels from second-top to bottom show different orientation angles for the buckled bar of 0°, 45°, and 90°, respectively, with respect to the major axis of the disk. Axes are in units of the initial exponential disk scale length. (From Debattista et al. 2004.)

to determine when the bar forms, when it buckles, and the evolution of disk properties such as mass density, morphological diagnostics (for any inclination angle of the disk and orientation of the bar), and the V/σ ratio. As an example, Figure 1.1 shows, for various disk inclination angles and tilt angles of the bar with respect to the disk major axis, the isophotal contours of the projected surface density of the system after the bar has formed and buckled. As already pointed out in, for example, Raha et al. (1991), for some projections, including but not uniquely for the edge-on one, the buckled bar looks very much like a normal (three-dimensional) "rounder-than-the-disk" bulge. Figure 1.2 shows, for two different simulations, how the systems would appear on the sky as observed from a specific line-of-sight

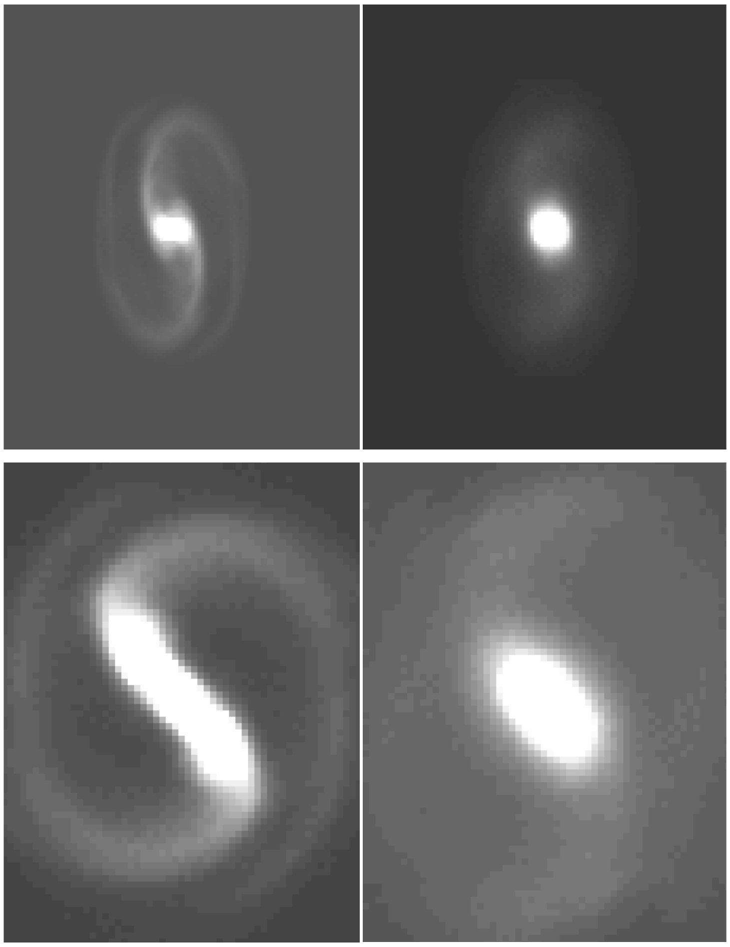

Fig. 1.2. A Hernquist halo simulation (upper panels) and a core halo simulation (lower panels). The images are taken before the buckling (left panels) and after the buckling (right panels) of the bars. The models have inclination angles of 60° and 30°, and bar orientation angles of 90° and 45°, respectively. (From Debattista et al. 2004.)

before and after the buckling of the bars. For the same two models, Figure 1.3 plots the initial surface density profiles (exponential by construction), the surface density profiles after the buckling of the bars, and the post-buckling ellipticity profiles of the systems. Figure 1.3 points out that an initially exponential disk that "nature" makes can be observed to be a more centrally concentrated structure at a later stage, after it has formed and buckled a stellar bar. The final, post-buckling profile in the simulations is well described by the sum of an outer exponential disk and an inner Sérsic component, as observed in real disk galaxies. If the denser-than-exponential profiles in the real late-type spirals were due to the effects of nurture rather than nature, the inner light/mass excesses in the late-type disks would be

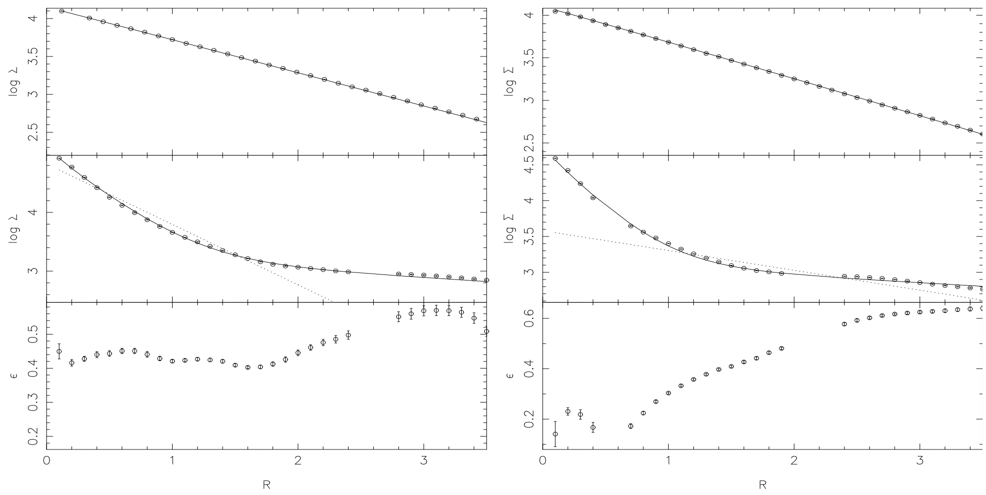

Fig. 1.3. For the same core halo (left) and Hernquist halo (right) models shown in Figure 1.2, we plot here the initial surface density profiles (upper panels: superimposed with the single-exponential fits), the surface density profiles after buckling (middle panels: dotted lines, the single exponential fits; solid lines, exponential plus Sérsic fits), and the ellipticity profiles after buckling (lower panels). The x-axis is in units of the initial exponential disk scale length. (From Debattista et al. 2004.)

better associated with "bulge" structures; that is, they would be the "bulges" produced by secular evolution of the disks, which has been extensively discussed in the literature.

Bars are not the only possible solution to increase the central densities in disk galaxies by means of processes that occur after the original baryonic collapse inside the dark halos: viscosity may be important (e.g., Lin & Pringle 1987), and also mergers, satellite accretion, dynamical friction of globulars, etc. Nonetheless, it is fair to conclude that, at this stage, the issue whether the disks are born as denser-than-exponential structures remains open. If this were the case, it will be important to quantify the systematic uncertainties on, for example, bulge scale lengths and luminosities, black hole masses and other galactic properties that are derived assuming that nature, when it makes a disk, makes it exponential.

1.6.2 Bulges

The investigations of the past few years indicate that even the most massive, early-type bulges are not $r^{1/4}$-law systems and have disklike imprints in their kinematics. How do we reconcile, under a common denominator, the differences between bulges and ellipticals with the quoted similarities of stellar population and scaling laws? It is certainly not clear what, for instance, the Mg_2 index and the velocity dispersion σ represent in the $\mathrm{Mg}_2-\sigma$ relation. Are the key parameters metallicity, age, or a combination of the two? Are they the depth of potential well, local physics of star formation, or, again, a combination of the two? Local physics imposes thresholds for star formation (e.g., Meurer et al. 1997), which is likely to have an impact on scaling laws such as the $\mathrm{Mg}_2-\sigma$ relation. Indeed, the same $\mathrm{Mg}_2-\sigma$

relation is observed to hold over orders of magnitude of scale lengths, in systems that are very different, ranging from elliptical galaxies to dwarf spheroidals (Bender, Burstein, & Faber 1993). The conclusion is that the $Mg_2 - \sigma$ and similar relations are certainly telling us something important about the formation of stellar systems over a large range of scales, but not necessarily that they all share a similar formation process.

On the other hand, the claims that violent relaxation is not a major player in the formation of bulges, based on the observed Sérsic profiles with $n \lesssim 3$ (Balcells et al. 2003) may also be premature. The consequence of violent relaxation during dissipationless processes such as stellar clumpy collapses (van Albada 1982), mergers of disk galaxies (Barnes 1988), satellite accretion onto disk galaxies (Aguerri, Balcells, & Peletier 2001) is to produce an $r^{1/4}$ profile. However, other studies of violent relaxation in a finite volume show deviations from the $r^{1/4}$ law (Hjorth & Madsen 1995). Furthermore, the same problem of separating nature from nurture may be relevant also in this context. Physical processes may occur during the Hubble time that modify the stellar density profiles in the centers of galaxies, including dynamical friction of globular clusters, dissipative accretion of matter, black hole-driven cusp formation, mergers of black holes (quantitative studies of the latter show that central mass deficits are created from the binding energy liberated by the coalescence of the supermassive binary black holes; see, e.g., Milosavljević et al. 2002, Ravindranath, Ho, & Filippenko 2002, and references therein). Numerical studies of these processes are still rather sketchy and do not explore a vast volume of parameter space; nonetheless, they make the point that the nuclear stellar density profiles may be modified by subsequent evolution. Quantitative work remains to be done to assess whether these or other processes can reproduce the $n \approx 3$ Sérsic profiles typical of the massive bulges and the weak trend between Sérsic shape parameter n and bulge luminosity. The possibility that the disks may not be purely exponential also introduces additional uncertainties on the derived bulge parameters, including the shape index n. If the outer disk can have a Sérsic shape with n values as steep as ~ 2.5, bulge-disk decompositions that use an exponential for the outer disks can systematically offset the bulge parameters. This could even open the question as to whether the observed sequence in n values between the late-type and early-type bulges is a pure bulge sequence, or, rather, at least in part a sequence of different underlying disk profiles.

Concerning support for bulge-building secular evolution processes inside preexisting disks, there is certainly at this point good evidence from high-resolution numerical experiments that the intrinsic evolution of the disks results in transformations of the disks, which can generate three-dimensional structures that resemble bulgelike components. Numerical studies (Pfenniger & Friedli 1991; Zhang & Wyse 2000; Scannapieco & Tisseira 2003; Debattista et al. 2004; see Fig. 1.3) also show that the bulgelike, three-dimensional structures that generally result from the evolution of the disks have the rather low-n Sérsic profiles typical of real bulges. MacArthur et al. (2003) report that simulations by D. Pfenniger (2002, private communication) of self-gravitating disks form bars that may later dissolve into bulgelike components, which show a nearly universal ratio of bulge-to-disk scale lengths, also in agreement with the observed correlations. In the simulations, the universal ratio of bulge-to-disk scale lengths is related to the stellar dynamics of the barred system, for example to the relative position of the vertical to horizontal resonances. There is an additional important ingredient that has been missing so far in the debate concerning the possibility that disk secular evolution processes play a substantial role in forming bulgelike structures: namely, the bulges that result from the secular evolution of the disks are, in contrast to what is commonly asserted,

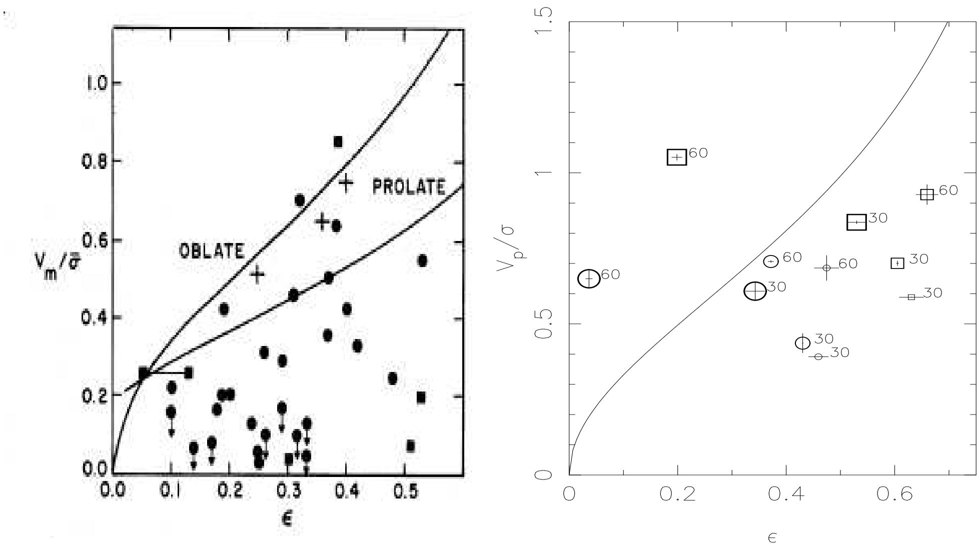

Fig. 1.4. V/σ versus ellipticity ϵ plane. The left panel reproduces Figure 2 of Davies & Illingworth (1983); points are the measurements for observed spheroids, both bulges (crosses), and ellipticals (filled circles and squares). The right panel shows a similar plot derived from our simulations. The oblate-rotator line is also plotted as a solid line. The data points in this panel refer to the end of the simulations, after the bars that have formed in the disks have buckled. The V/σ and ϵ values for the "buckled bars" are derived by averaging the relative profiles inside the half-light radii of the inner Sérsic components that are necessary, in addition to the outer exponential disk components, to obtain good fits to the surface density profiles after buckling. Circles are used for the logarithmic and squares for the Hernquist halo potentials. The size of the symbols refers to the bar orientation angles (90° largest, 45° intermediate, 0° smallest). The disk inclination angle i is explicitly indicated close to symbols. From certain viewing angles and bars orientation angles, buckled bars are indistinguishable from normal spheroids on the V/σ versus ellipticity ϵ plane. (From Debattista et al. 2004.)

not necessarily dynamically cold, "disklike" stellar systems. Due to the fact that eccentric orbits are quickly erased by shocks (Friedli & Benz 1995), the secular evolution of mostly gaseous disks indeed produces cold stellar structures such as the pseudo-bulges discussed by Kormendy (1993); however, the buckling of stellar bars, for example, can produce structures that are, at least from certain viewing angles, indistinguishable from the alleged "normal" bulges in classical diagnostic planes such as the V/σ-ϵ plane. This is shown in Figure 1.4, where the locations on the V/σ-ϵ of a few representative buckled bars from our simulations are shown (right panel) in comparison with what is typically considered the *bona fide* bulge behavior (left panel, figure from Davies & Illingworth 1983).

In summary, from Figures 1.1–1.4, it is evident that, depending on the viewing angle, buckled bars can appear as structures that are simultaneously rounder than the surrounding disks, photometrically identifiable as additional components in excess of outer exponential disks, and kinematically similar to what are considered to be "*bona fide* bulges." In this light, it seems appropriate to question indeed what is a meaningful definition for a *bona fide* bulge. Clearly, the situation is more complex than what is captured in the theorist-versus-observer dichotomy discussed by Böker et al. (§1.4). First, from an observational perspective, even early-type, *bona fide* bulges have been claimed to be thickened disks (Falcón-Barroso et al. 2003). Second, from a theoretical perspective, evolutionary disk processes such as the buckling of progenitor bars inside the disks can produce structures that, in contrast to common belief, are dynamically similar to the *bona fide* bulges that should be the benchmark for the comparison. Thus, as with the photometric classification, even the kinematic classification of bulges is quite fuzzy. Ultimately, this is due to the lack of a proper physical boundary between structures that are forced into different categories by what may be unfolding into an obsolete and confusing classification scheme.

1.6.3 The Nature and Role of Nuclei and Central Black Holes

Recent surveys show that central, distinct, compact components, in addition to the disk and the bulge, are present in the large majority of disk galaxies of all Hubble types. Many are clearly star clusters with no AGN contamination. This includes, for example, the "naked" ones in the late-type disks studied by Walcher et al. (2004) and probably the relatively faint population of nuclei embedded in the relatively clean surroundings of the exponential-type bulges (Carollo et al. 1997c, 1998). AGNs are known to be rare in late-type galaxies (Ho, Filippenko, & Sargent 1997; Ulvelstad & Ho 2002; Ho 2004). An AGN component may, however, be present in a fraction of the nuclei. This would be statistically consistent with the fact that about 70% of spirals host a distinct nucleus, and about half of them are known to host some form of AGN, even if weak (Ho et al. 1997). Some of the point sources embedded in the early-type bulges of Balcells et al. (2003) may also have an AGN origin or component; pointlike sources associated with AGNs are seen in massive elliptical galaxies (Carollo et al. 1997a, b; Ravindranath et al. 2001).

The young stellar ages plus high velocity dispersions of the central star clusters of late-type disks reported by Walcher et al. (2004) may certainly imply a large spread in stellar population ages, and thus an iterative mass assembly and star formation for the central star clusters, as discussed by the authors. However, the nuclei that are typically selected for the spectroscopic investigations populate the bright end of the luminosity distribution of nuclei. Walcher et al. (2004) stress that in their sample there is no indication that brighter means younger; nevertheless, it is still possible that selection effects are important and that fainter nuclei may have less complex mass assembly and star formation histories. A wide range of star formation histories would be more consistent with a process of growth of central star clusters that is regulated by local physics, for instance by the amount of fuel (either gas or smaller star clusters) available at various epochs in the circumnuclear regions, the angular momentum distribution or orbital structure of this "fuel," and the physical state of the central regions of the disk (e.g., its density or dynamical temperature, in turn determining or originating from the steepness of the gravitational potential, the conditions to develop non-axisymmetric perturbations on small scales, etc.). Furthermore, it is still unknown whether fuel-starved, silent AGN engines—massive black holes—may be present in the central star clusters (e.g., Marconi et al. 2003). The question of whether massive black holes reside in general in the centers of star clusters is far from settled. The case of G1, a globular cluster in Andromeda in which a central black hole of the mass expected from the linear extrapolation of the relationship reported for the massive spheroids (e.g., Gebhardt et al. 2000) has been detected (Gebhardt, Rich, & Ho 2002), argues for the presence of massive black holes in the centers of star clusters, and supports the suggestion that black holes are ubiquitous and proportionally sized in all spheroids, from mass scale of globular clusters to elliptical galaxies. A small, $\sim 10^{4-5} M_{\odot}$ black hole is found embedded in the central star cluster of NGC 4395, one of the least luminous and nearest known Type 1 Seyfert galaxies (Filippenko & Ho 2003). On the other hand, the nondetection of a central black hole in the central star cluster of M33 contrasts with the G1 case and argues for the absence of massive black holes in the centers of the distinct nuclei of bulgeless disks. Gebhardt et al. (2001) discuss that, if the mass of a central black hole in the nucleus of M33 was related to its velocity dispersion in the same way that the known supermassive black holes are related to the dispersions of their bulges, then a black hole with mass in the range $\sim 7 \times 10^3 - 6 \times 10^4 M_{\odot}$ would be expected, well above the measured upper limit of 1500 $M_{\odot}$. Solutions to this inconsistency include those suggested by the authors: the relationship between the mass of the black hole and the velocity dispersion of the host spheroid may be nonlinear; the conditions to make a massive black hole were better in the earlier, denser Universe, when the stars in G1 were made; or M33's young nucleus has not had enough time to create its own black hole. Given the observational uncertainties, other possibilities remain. It could be that G1 is not a star cluster but a harassed spheroidal galaxy [a fact mentioned by Gebhardt et al. (2002) but not considered by the authors as the cause for the discrepancy]. Another possibility is that at least in small-sized spheroids such as star clusters, black holes may not be ubiquitous, or there may not exist a tight correlation between black hole mass and spheroid mass. Or perhaps normal star clusters and the central star clusters in disk galaxies have a different origin.

The case of M33 serves also as a smoking gun in another context. Kormendy & Gebhardt (2001; see also Kormendy et al. 2004) report that the same correlation between the mass of the central black hole and the host luminous spheroid holds for galaxies with both "normal" and kinematically cold, disklike bulges (i.e., the "pseudobulges" discussed by Kormendy 1993). In contrast, M33, a pure disk galaxy with no bulge component of any sort, is indeed found to lack a black hole. Kormendy & Gebhardt (2001) conclude that the basic requirement for making a supermassive central black hole appears to be that the galaxy is capable of forming some kind of dense, bulgelike structure, whatever its nature. Reinterpreting this comment in the light of the bulge/dense-disk conundrum discussed above, the results of Kormendy & Gebhardt (2001) and Gebhardt et al. (2001) may imply that the requirement for making a supermassive central black hole is that the galaxy is capable of reaching sufficiently high central baryonic densities. Either way, from these analyses it appears that black hole masses are not correlated with the total gravitational potential of the disks, and thus of the host dark matter halos. A contrasting report, however, comes from Ferrarese (2002) and Baes et al. (2003), who claim a tight correlation between the circular velocities of galaxies and the masses of their central supermassive black holes, and thus an intimate link between the black holes and the host dark matter halos. Supermassive black holes do form in some pure disk systems, as shown by Filippenko & Ho (2003) for the case of NGC 4395. However, these authors stress that in this galaxy the estimated black hole mass is consistent with the $M_{\bullet} - \sigma$ relation of Tremaine et al. (2002), if the central cluster is considered in lieu of the bulge. For a $\sigma = 30$ km s^{-1}, a good upper limit for the velocity dispersion of central star cluster in NGC 4395, this relation predicts a $M_{\bullet} = 6.6 \times 10^4 M_{\odot}$, consistent with the mass independently estimated from the AGN properties (Filippenko & Ho 2003). Furthermore, it remains a fact that M33, possibly the best candidate to test for the validity of a correlation between the black hole mass and the dark matter halo mass, appears not to support it. As stressed by Gebhardt et al. (2001), if a black hole in M33 were indeed related to the dark matter potential well, then M33 should contain a black hole of mass significantly in excess of $10^6 M_\odot$, which it does not. It may be best to wait for the observational picture to be cleared up before attempting interpretations of the claimed correlation between black hole and dark halo masses.

Finally, given the large frequency of occurrence of nuclei in disk galaxies and the generally accepted idea of hierarchical galaxy assembly, an interesting question is whether the formation and evolution of the nuclei of disk galaxies play any relevant role in the formation of supermassive black holes in the centers of galaxies. More generally, a key question for the future is whether the nearly ubiquitous nuclei are a nuance or rather an important ingredient in the formation process of disk galaxies.

1.7 Concluding Remarks

In summary, at a resolution of typically a few tens to a few hundred parsecs, the local disk galaxy population appears to host bulges that more and more resemble disks, and disks that more and more resemble bulges. Disks may be denser than exponential, and bulges may be less steep than de Vaucoluleur's structures. Bulges are claimed to have the kinematics of thickened disks, and buckled bars can be as dynamically hot as the structures claimed to be "true" bulges. The average stellar population properties (i.e., stellar ages and metallicities) remain the only surviving distinction between "massive" and "small" bulges and, more generally, between massive bulges and the centers of disks. This could certainly be an indication of different formation processes, but could also be the result of similar processes occurring at different epochs in the Universe (and thus naturally generating a positive correlation between stellar densities and ages). In my view, what is needed at this point is a shift of the debate from the arena of morphological classifications, where bulges and disks are distinct entities and the question "what is the origin of bulges' is kept distinct from the question "what is the origin of disks," to one where disk galaxies are studied as a whole without the constraints of a rigid classification scheme. The historical focus on morphology, while highlighting many details in the trees, may in fact have hidden the true nature of the forest. The expected outcome will be a renewed concept of the "Hubble sequence" that will be ultimately be based on physical rather than morphological considerations. Clarifying what we really see nearby as the endpoint of the galaxy evolution process is essential in order to meaningfully answer how the distant progenitors, which are seen in the most remote regions of the Universe, transform themselves to become the descendants that populate our own surroundings.

Acknowledgements. I thank L. Ho for the invitation to this very stimulating meeting, and especially for his patience waiting for this manuscript. I am grateful to my collaborators, V. Debattista, L. Mayer and B. Moore for kindly making available some of our results prior to publication. Many thanks to F. van den Bosch and S. Lilly for comments on a previous version of this manuscript.

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