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Structure, Kinematics, and Dynamics of Bulges

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Abstract. A historical review of our understanding of bulges is first presented, highlighting similarities and differences between bulges and ellipticals. Then, some topics of current interest are reviewed, bypassing stellar population questions and focusing on structural and dynamical issues relating bulges and disks. The topics are: i) the fundamental plane; ii) the evidence for two classes of bulges, $R^{1/4}$ and exponential, and its significance for bulge formation; iii) the three-dimensional structure of bulges, in particular the relation between boxy/peanut-shaped bulges and bars; iv) the nuclear properties of bulges, and their possible effects on bulge dynamics and secular evolution; and v) the large-scale mass distribution and evidence for dark matter in bulges. To conclude, new prospects offered by wide-field integral-field spectroscopy and other instrument developments (space and ground-based) are discussed.

1. Introduction

Both figuratively and literally, bulges are central to our understanding of most disk galaxies. The so-called "super-thins" apart, bulgeless disks with extreme axial ratios (Karachentsev, Karachentseva, & Parnovskij 1993), most disks possess a central spheroidal-like component called the bulge (better defined as the central excess over the inward extrapolation of the outer exponential disk; Carollo, Ferguson, & Wyse 1999). In fact, the bulge-to-disk ratio is a defining property of the Hubble classification for spirals. In many cases, the bulge dominates the central potential, it determines the position of major resonances, and bulges are now known to be intimately linked to massive central black holes (BHs; Magorrian et al. 1998). Bulges thus play an active role in the structure, dynamics, and evolution of the galaxies in which they are embedded.

Writing an exhaustive review in the space allocated is impossible, so only selected topics related to the structure, kinematics, and dynamics of bulges will be discussed. Issues regarding stellar populations will mostly be left out, and clues to bulge evolution shall be noted only when directly relevant to the issue at hand. The common thread will be to emphasize similarities and differences between ellipticals and bulges on the one hand, and bulges and disks on the other. Topics to be discussed include a brief historical review (§ 2.), the fundamental plane (FP) of bulges (§ 3.), their light distribution (§ 4.), 3D structure (§ 5.), nuclear properties (§ 6.), and large-scale mass distribution (§ 7.). The conclusions (§ 8.) will illustrate the perspectives offered by panoramic integral-field spectrographs and new or recent instruments.

2. Bulges and Ellipticals: A Historical Point-of-View

It is fair to say that our basic understanding of the structure and dynamics of bulges and ellipticals stems from work done in the 1970s and early 1980s. A few references will be used to illustrate key developments in the field.

Until the late 1970s, ellipticals and bulges were thought to be very similar because of similar light profiles, stellar content, and kinematics. Hints of scaling relations were also beginning to appear. de Vaucouleurs (1958) showed that Andromeda's bulge followed the $R^{1/4}$ surface brightness profile of ellipticals. Faber (1977) showed that ellipticals and bulges (S0s and Ss) had similar stellar populations, sharing the same colors, Mg_2–M_B, and NaD–Mg_2 relations. Faber & Jackson (FJ; 1976) discovered a projection of the FP ($L \propto \sigma^4$), shared by both ellipticals and bulges (taken here as S0s and M31), and showing no discontinuity in mass-to-light ratio M/L. Of course, other properties were known to differ. From their axial ratio distributions, Sandage, Freeman, & Stokes (1970) noted that ellipticals are consistent with a large range of intrinsic flattening, $q \equiv b/a \approx 1.0 - 0.3$, while lenticulars and spirals must all have intrinsically flat disks, with a nearly constant axial ratio ($q \approx 0.25$). Furthermore, some of the above similarities were later proven too simplistic.

Because of the flattened light distribution of ellipticals, oblate spheroidal models with isotropic velocity dispersions were first constructed (e.g. Lynden-Bell 1962, Prendergast & Tomer 1970). Wilson (1975) showed that, based on the Ostriker & Peebles (1973) criterion, models flatter than E4 would be unstable to axisymmetric perturbations. The crucial developments, however, came with the first rotation curves based absorption lines, able to probe the stellar kinematics. Illingworth (1977) demonstrated in a distance-independent way that ellipticals have only 1/3 (on average) the rotation required by oblate isotropic models. Rotation thus contributes little to their total kinetic energy. Schechter & Gunn (1979) extended these results and showed that some ellipticals possess significant minor-axis rotation and isophotal twists. It was thus clear that ellipticals were triaxial ellipsoids (or oblate spheroids) flattened by anisotropic velocity dispersions, not rotation. Binney (1976, 1978) had already shown that anisotropies could be preserved in the collapse of a (non-spherical) protogalactic cloud.

These results prompted a new look at bulges. It was quickly realized that many bulges are not well represented by $R^{1/4}$ light profiles, some even showing an exponential decline (e.g. NGC4565; Jensen & Thuan 1982). Bulges also appeared to be rotating more rapidly than the bright ellipticals studied so far (Kormendy & Illingworth 1982), suggesting formation through dissipational collapse rather than merging (the spin parameter λ is much larger than expected from tidal torques, 0.3 rather than 0.05). Nevertheless, Davies et al. (1983) showed that low luminosity ellipticals rotate as fast, both being consistent with rotationally flattened isotropic oblate models (see Fig. 1). This clearly suggested a continuum in the structure and dynamics of spheroids as the luminosity is decreases.

Lynden-Bell (1967) provided a physical basis for the aforementioned models, showing that violent relaxation (i.e. rapid collapse) leads to a distribution function $f(E, L_z) \propto \exp(-\mathrm{cst}.E + \mathrm{cst}.L_z)$, where E and L_z are the specific energy and angular momentum around the symmetry axis, and the L_z term is non-zero for rotating systems only. In fact, for a certain concentration index, King's (1966) models reproduce well the $R^{1/4}$ law over a large range of radii.

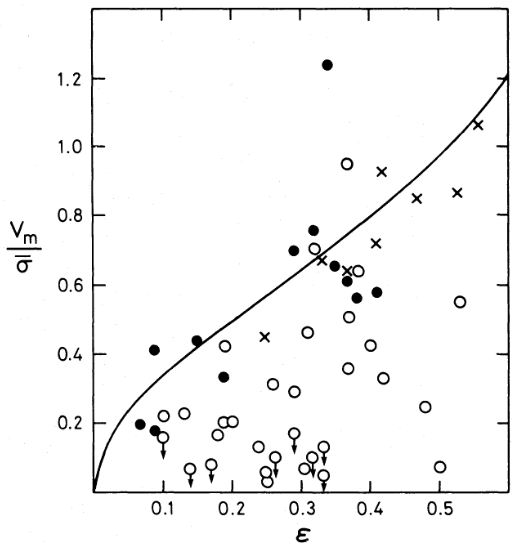

Figure 1. Rotational support of spheroids. The ratio of the maximum velocity of rotation to the average value of the dispersion within $^1/_2\, R_e$, $V_m/\bar{\sigma}$, is plotted as a function of the projected ellipticity near R_e, ϵ. The solid line represents isotropic oblate rotator models (Binney 1978). *Open circles:* Bright ellipticals ($M_B \le -20.5$). *Filled circles:* Faint ellipticals ($M_B > -20.5$). *Crosses:* Bulges. Both bulges and faint ellipticals are consistent with isotropic oblate spheroid models. Reproduced with permission from Davies et al. (1983).

3. Fundamental-Plane of Bulges

Both "early" bulges and ellipticals follow a common relation, more general than the FJ relation, known as the FP: $\log R_e = \alpha \log \sigma + \beta \log I_e + \gamma$, where R_e is the effective radius, σ the central velocity dispersion, I_e the effective surface brightness, and α, β, and γ constants (Djorgovski & Davis 1987, Dressler et al. 1987). If the systems are in virial equilibrium (as expected), have a constant M/L, and form a homologous family (i.e. their properties scale simply with luminosity or mass), we expect $\alpha = 2$ and $\beta = -1$ (γ varies with distance). In practice, the coefficients differ from the virial expectation and depend somewhat on their definitions and measurements. Jørgensen, Franx, & Kjærgaard (1996; Fig. 2) obtain $\alpha = 1.24$ and $\beta = -0.82$ in Gunn r, with a scatter of 0.07 in $\log R_e$ (17% error on individual distances). Crucial for determining distances, the slope is constant among clusters (independent of richness, T_{gas}, $\sigma_{cluster}$, etc). The scatter is real, higher for S0s (bulges), and is unlikely due to disks or projection effects (residuals uncorrelated with the shape of the light distribution).

Departures from the virial FP can be assigned to a varying mass-to-light ratio, $M/L \propto R_e^{-1-1/\beta}\, \sigma^{2+\alpha/\beta}$ ($M/L \propto R_e^{0.22}\, \sigma^{0.49}$; Jørgensen et al. 1996). Despite a large scatter, this is an important statement, relating the stellar populations of spheroids to their structural parameters. It is probably unaffected by dark matter, since spheroids appear baryon dominated within one R_e (to be contrasted with the Tully-Fisher relation for spirals; Freeman, these proceedings).

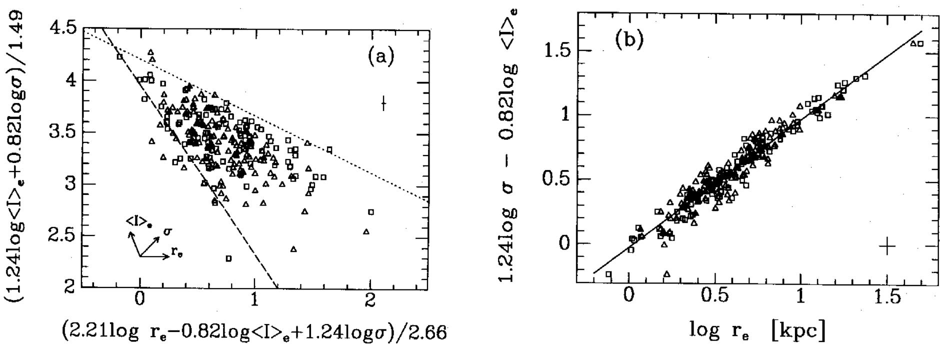

Figure 2. Fundamental plane of spheroids in Gunn r. *Left:* Face-on view. The dashed line represents a selection effect (limiting magnitude), while the dotted line does not. *Right:* Edge-on view. *Boxes:* Ellipticals. *Triangles:* Bulges (S0s). Typical error bars are shown in each panel. Reproduced with permission from Jørgensen et al. (1996).

A relation between σ and the line-strength index Mg_2 (or broadband colors) also exists, varying slightly among clusters, possibly due to age or most likely metallicity variations (Jørgensen et al. 1996). M/L thus varies between clusters (bad for distances if not accounted for), and bulges and ellipticals do not all have the same probability distribution of characteristic parameters. The scatter in the Mg_2 "FP" is also real, implying some scatter in the stellar populations.

Although "early" bulges populate the FP slightly differently from ellipticals (as do compact ellipticals, dwarf ellipticals, and dwarf spheroidals), they follow the same Mg_2–σ relation, and their properties again suggests a continuation of the elliptical sequence, indicative to some of a merging sequence with varying degrees of dissipation (see Bender, Burstein, & Faber 1993).

4. Light Distribution of Bulges

So far, we have assumed structural homology. Sersic's (1968) law allows to characterize structural differences between galaxies using the the shape parameter n: $I(r) \propto \exp[-(r/r_0)^{1/n}]$, where $I(r)$ is the surface brightness profile and r_0 some characteristic radius. For $n = 4$ and $n = 1$, we retrieve the usual $R^{1/4}$ and exponential profiles. Imposing the $R^{1/4}$ law leads to biased measurements of R_e and I_e (and σ) and affects the tilt of the FP; the departure from virial expectation is reduced when using Sersic profiles and deprojected quantities.

Galaxies and bulges are better fitted by Sersic law and show a great variety of shapes: n extends from over 10 to 0.5 as one goes from brightest cluster galaxies to normal ellipticals and S0s, bulges, and dwarfs (Graham et al. 1996). For bulges alone, n varies systematically from 6 to 1 from early to late-type systems (high to low bulge-to-disk ratio), with weaker trends as a function of luminosity and size (see Fig. 3; Andredakis, Peletier, & Balcells 1995). This again suggests a similar formation mechanism for all spheroids, as different mechanisms for early and late-type systems (or normal and pseudo bulges, see below) would likely lead to a bimodal distribution of n.

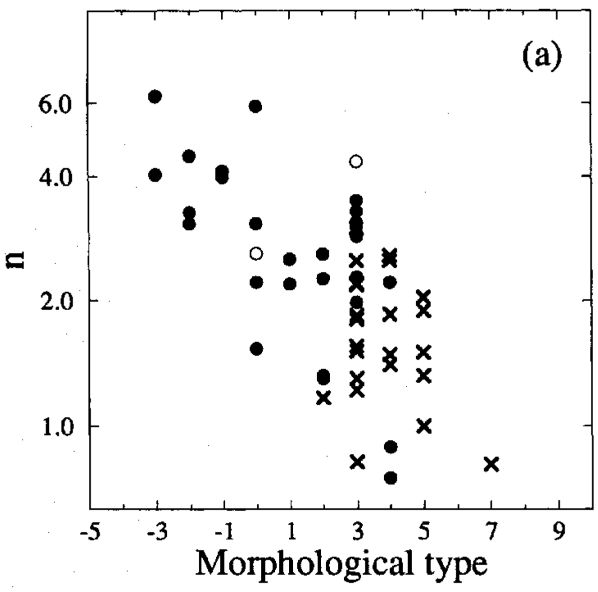

Figure 3. Shape of bulges. Sersic's (1968) shape parameter n plotted as a function of the host galaxy morphological type. *Circles:* Andredakis et al. (1995) sample. *Crosses:* Kent (1986) sample. Open symbols represent barred galaxies. No error bars are plotted for clarity. Reproduced with permission from Andredakis et al. (1995).

In violent relaxation, galaxies with deep central potentials lead to high n (Hjorth & Madsen 1995); conversely, the central potential increases with n (Ciotti 1991; both for spherical isotropic models). For bulges, the formation or interaction with the disk may affect the density distribution. The continua of properties mentioned above thus somewhat support the suggestion that all spheroids harbor a disk (e.g. Burstein et al. 2001), although their influence is probably small in large ellipticals and there are few indications of disks in dwarfs.

Kormendy (1993) also argues that a number of bulges, referred to as pseudo-bulges, show structural and kinematic evidence for disk-like dynamics. These include: i) σ smaller than expected from the FJ relation; ii) fast rotation, with V/σ above the isotropic oblate rotator line in the $V/\sigma - \epsilon$ diagram; iii) bulges as flat as the disk; iv) spiral structure within $R^{1/4}$ profiles; and v) substantial population I material in later types. This suggests that pseudo-bulges may really be high surface brightness central disks, and that disks may have a steeper inner light profile than the inward extrapolation of an exponential. A transition from bulge to disk-dominated properties is suggested at types Sb–Sbc.

This picture is consistent with simulations of gas flow in barred galaxies, which lead to high (and flat) central gas concentrations, possibly feeding a central BH and forming stars (e.g. Friedli & Benz 1993, Heller & Shlosman 1994). The bulge and disk scalelengths also correlate, independently of type, further suggesting that at least some bulges grow secularly out of disk material (de Jong 1996). Evolution is then more than the simple aging of the stellar populations.

5. Three-Dimensional Structure of Bulges

We have argued that bulges are oblate spheroids, but it has long been known that many bulges show a boxy or peanut-shaped (B/PS) morphology (e.g. Shaw 1987). The vast majority of these are probably bars seen edge-on. N-body models show that shortly after a bar forms, it buckles, thickens, and appears almost round, peanut, or boxy when seen end-on, side-on, or at an intermediate angle. The evolution strongly depends on the (dark) halo-to-disk mass ratio, but simulations always result in a B/PS bulge with an exponential vertical light profile (e.g. Combes et al. 1990). The thickening is probably due to vertical heating of the disk through resonant scattering of orbits by the bar (vertical inner Lindblad resonance (ILR)): $\Omega_p = \Omega - \nu_z/2$, where Ω_p is the bar pattern speed and Ω and ν_z the stellar rotation and vertical oscillation frequencies. The vertical and horizontal ILRs also converge, so that $\kappa \approx \nu_z$ where the maximum thickening occurs (κ is the epicyclic frequency), and the peanut shape is sustained by orbits trapped around the 3D generalization of the (2D) x_1 family.

B/PS bulges are not found preferentially in groups or clusters, but they do show an increase of nearby companions. Although accretion (soft merging) can lead, in principle, to B/PS bulges (Binney & Petrou 1985), it probably accounts only for a minor fraction, perhaps related to the "thick boxy bulges" of Lütticke & Dettmar (1999). Hybrid scenarios, where the formation of a bar is triggered by an interaction, are also possible (Mihos et al. 1995). N-body models show cylindrical rotation in the inner parts of B/PS bulges, as suggested by the few observations available (e.g. NGC4565; Kormendy & Illingworth 1982), the fraction of B/PS bulges and barred disks are consistent (Lütticke, Dettmar, & Pohlen 2000), and B/PS bulges show plateaus in their light profiles. However, to prove that B/PS bulges are related to bars, and are thus triaxial, one really wants to probe the potential, requiring kinematics in the bulge region.

Periodic orbits provide a zeroth order view of stellar kinematics. Because of the non-homogeneous distribution of the orbits (see, e.g., Contopoulos & Grøsbol 1989), clear signatures of non-axisymmetry are seen in the position-velocity diagrams (PVDs) of edge-on barred disks (Bureau & Athanassoula 1999). But stars can move on trapped or chaotic orbits, washing out PVD substructures, and more realistic N-body models indeed reveal subtler signatures (Bureau & Athanassoula, in preparation). Gas, however, responds very strongly to a non-axisymmetric potential. Shocks along the bar cause inflow, deplete the gas in the outer bar regions, and lead to characteristic gaps in the PVDs (if a nuclear spiral is formed, requiring an ILR; Kuijken & Merrifield 1995, Athanassoula & Bureau 1999). Line-ratios can also help identify bars (shock versus photoionization). Merrifield & Kuijken (1999) and Bureau & Freeman (1999) applied these diagnostics and showed an almost one-to-one correspondence between B/PS bulges and large-scale bars (Fig. 4), although a few cases may be due to accretion. The strength of the bar also correlates with the boxiness of the isophotes. Thus, contrary to ellipticals, where it is caused by anisotropic velocity dispersions, triaxiality in bulges is due to high rotation (bar instability).

As face-on galaxies often show photometrically distinct bars and (rounder) bulges, it is still unclear whether the above thick bars are truly one with the bulge, or whether a more axisymmetric bulge is simply buried within them. A complete 3D picture of barred galaxies (and bulges) is thus still missing.

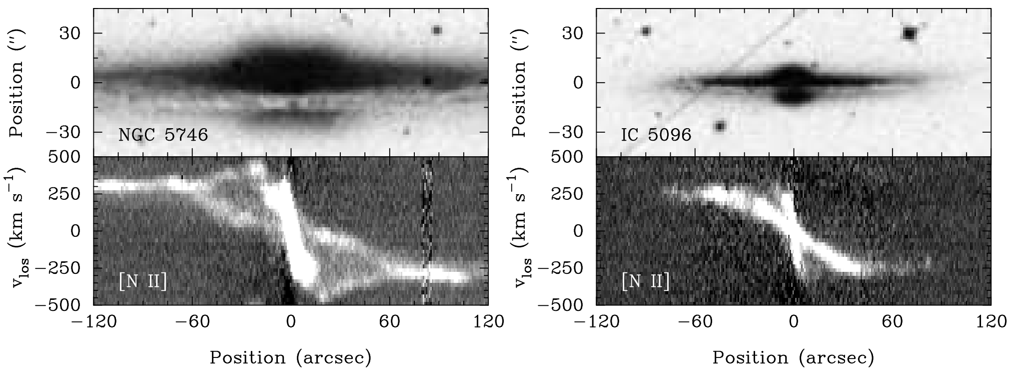

Figure 4. Bar signature in B/PS bulges. Image and ionized gas PVD (on the same scale and along the major-axis) for two B/PS bulges. *Left:* NGC5746, probably seen side-on. *Right:* IC5096, probably seen end-on. Adapted from Bureau & Freeman (1999) with permission.

6. Nuclear Properties of Bulges

While the large-scale structure and kinematics of nearby bulges can be studied from the ground, HST is required to reach scales of a few tens of parsecs. An HST/WFPC2 study of a large sample of bulges (mostly unbarred, Sa–Sbc) by Carollo et al. (1997, 1998) reveals a large variety of nuclear properties, even among early types. Some "classical" bulges exist, but in half the cases a bulge is not even clearly detected. i) Many early-type galaxies show no evidence for a smooth bulge (also dust lanes, spiral structure, etc); ii) 30% of bulges have an irregular central bright component with scattered star forming regions. Other nuclear star formation occurs, sometimes in ring-like structures, but it is unclear whether it is associated with the bulge or inner disk; iii) for types later than S0/a, half the objects have a resolved, compact central source (often associated with an elongated structure), the luminosity of which correlates with that of the host galaxy but not the type (typically brighter in star forming objects); iv) the brightest compact sources appear similar to young star clusters in the $M_V - R_e$ plane, while fainter sources are intermediate between ellipticals and $R^{1/4}$ bulges and globular clusters, possibly indicating an age sequence. Those sources are photometrically distinct from their surroundings and are not a simple steepening of the light profile. These facts suggest a late formation epoch for some bulges, possibly in disk-driven dissipative accretion events.

The nuclear light profiles of spheroids (bulges and ellipticals) is well described by the cusp slope γ ($I(r) \propto r^{-\gamma}$ as $r \rightarrow 0$; Byun et al. 1996). In the above sample, $R^{1/4}$-like bulges have cusps and nuclear densities similar to ellipticals (at a given spheroid luminosity L_s), and also steeper cusp slopes as L_s is lowered (Faber et al. 1997, Carollo & Stiavelli 1998). Exponential-like bulges show the same (weaker) dependence on L_s, but they have smaller cusps and nuclear densities at a given luminosity (Fig. 5). As a group, they thus break the general trend among spheroids of increasing density with decreasing luminosity, a rare indication for a different formation mechanism. This does not indicate a simple evolution along the Hubble sequence, however, as it holds true for a given type.

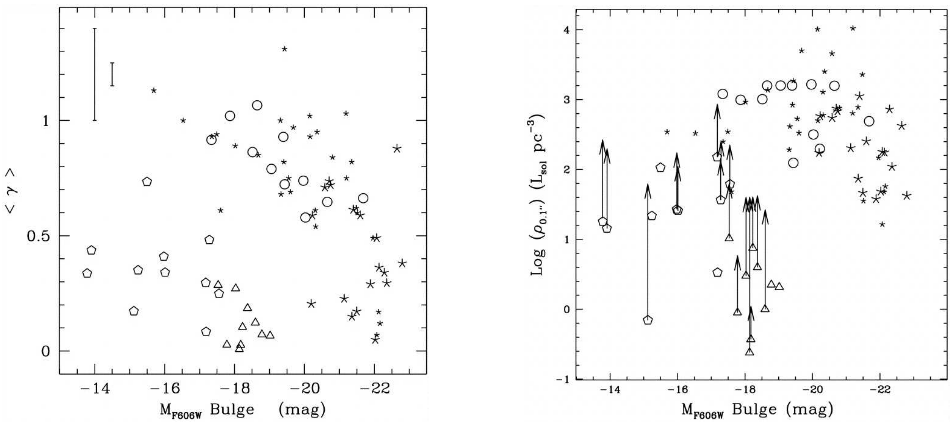

Figure 5. Nuclear cusp slopes and densities of spheroids. *Left:* Average logarithmic cusp slope ($0\farcs1$–$0\farcs5$) versus spheroid absolute magnitude. Error bars are shown for galaxies with and without a central compact source. *Right:* Stellar density at $0\farcs1$ (from deprojected analytic fits) versus spheroid absolute magnitude. *Triangles and pentagons:* Exponential-like bulges. *Circles:* $R^{1/4}$-like bulges. *Asterisks:* Ellipticals. Reproduced with permission from Carollo & Stiavelli (1998).

Magorrian et al. (1998) proposed the first central BH mass $M_\bullet$ to spheroid mass M_s (or spheroid luminosity L_s) relation, showing that power-law galaxies (steep cusps) have smaller $M_\bullet$ and M/L than core galaxies (shallow cusps). But the masses, based on ground-based kinematics and two-integral axisymmetric dynamical models, were overestimated. Using HST/STIS kinematics (resolving the sphere of influence of the BH) and three-integral models (allowing velocity anisotropy near the center) reduces the masses by a few. Essentially all galaxies require $M_\bullet \sim 0.001\,M_s$, suggesting a universal baryon fraction going in the BH. $M_\bullet$ correlates significantly better with L_s than the total galactic luminosity, indicating that BHs are not related to disks. The correlation is also independent of bulge type ($R^{1/4}$, exponential, pseudo), suggesting a close link between BH and bulge (spheroid) formation, independently of how the latter proceeds.

The relation between $M_\bullet$ and (some measure of) the central velocity dispersion σ is much tighter, although its exact dependence is debated: $M_\bullet \propto \sigma^{3.8-4.8}$, with a steep slope favored (Gebhardt et al. 2000a, Ferrarese & Merritt 2000, Merritt & Ferrarese 2001). The scatter of ≈ 0.3 dex (at fixed σ) is consistent with observational errors, indicating negligible intrinsic scatter. The previous relation with M_s can now be "understood", since $M_s \underset{\sim}{\propto} L_s^{5/4}$ (Faber et al. 1987) and $L_s \underset{\sim}{\propto} \sigma^4$ (FJ), hence $M_s \underset{\sim}{\propto} \sigma^5$ also. Bulges (spheroids) can now be seen as populating a 2D plane in a 4D space ($\log M_\bullet$, $\log R_e$, $\log \sigma$, $\log L$), the $M_\bullet - \sigma$ relation being an edge-on projection of this plane (while the $M_\bullet - L_s$ relation is not, thus the larger scatter). BH masses predicted from the $M_\bullet - \sigma$ relation are consistent with reverberation mapping measurements in active galactic nuclei (AGN; Gebhardt et al. 2000b, Ferrarese et al. 2001), indicating a close relationship between quiescent and active BHs, and strengthening the link between BHs, AGN, and bulge (spheroid) formation (e.g. Silk & Rees 1998).

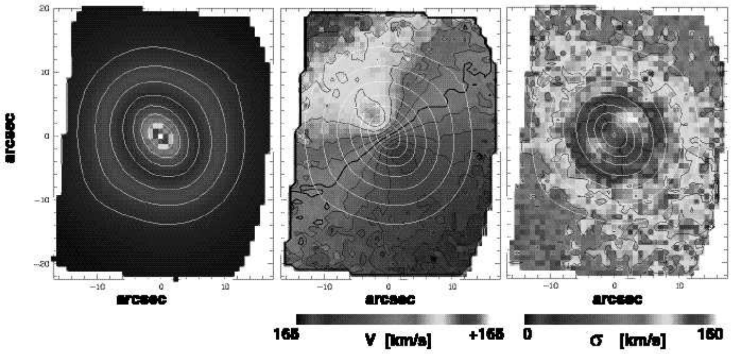

Figure 6. SAURON stellar kinematics of the SB0 galaxy NGC3384. *Left:* Reconstructed intensity map. *Center:* Velocity. *Right:* Velocity dispersion. Not shown are the Gauss-Hermite moments h_3 and h_4 (skewness and kurtosis of the velocity profiles), and the line-strength indices Hβ, Mg$_b$, Fe5015, and Fe5270 (stellar populations). The data clearly reveal a confined, cold kinematic component inside the bulge. Reproduced with permission from de Zeeuw et al. (2002).

There have been many suggestions that bars can be destroyed by central masses, secularly building bulges over many generations, and moving galaxies along the Hubble sequence (e.g. Norman, Sellwood, & Hasan 1996). BH masses reported are however an order of magnitude lower than required ($\sim$0.1% of M_s rather than a few). The central stellar clusters discussed above do have the right masses, but they would prevent bars from (re-)forming in late-type exponential bulges, inhibiting their growth and evolution into early-type $R^{1/4}$ bulges unless there is a substantial accretion of cold material (the same applies to BHs). The omnipresence of bars ($\gtrsim$ 70% of galaxies; e.g. Seiger & James 1998) implies a very fast duty cycle, however, which seems unlikely. At the moment, the evidence is thus against bar (destruction)-driven secular evolution in bulges.

7. Large-Scale Mass Distribution of Bulges

There is little to say about the (very) large-scale mass distribution of bulges, i.e. their dark matter content, as little is known. When there is neutral hydrogen and/or ionized gas, the usual kinematic tracers in disk galaxies, it often has a complicated geometry or is disturbed. As shown by Capaccioli et al. (1993), it is extremely hard to push traditional long-slit spectroscopy with integrated light to significant radii ($\gtrsim 2R_e$). They report for NGC3115 an increase in M/L from 6 to more than 10 as r goes from 1 to $2R_e$. Contrary to elliptical galaxies (e.g. Hui et al. 1995 for Cen A), there has been little use of globular clusters (GCs) and planetary nebulae (PN) as (stellar) tracers in bulges. Using GCs in NGC3115, Kavelaars (1998) shows that $M/L \approx 19$ at $5R_e$, suggesting the presence of dark matter in the halo. This is assumed to be generic but should be verified. The GC system also shows a red rapidly rotating metal rich thick disk system and a blue slowly rotating metal poor halo system, which is not unusual. Results from polar-rings and other objects probing the potential perpendicular to the equatorial plane are discussed in detail by Sparke (these proceedings).

8. Conclusions and New Perspectives

Since this is a review, conclusions will be short. Already in the early 1980s, a continuum between bright ellipticals, low-luminosity ellipticals, and bright bulges had been demonstrated (Davies et al. 1983). Now, a continuity in the structural and kinematic properties of bright bulges (generally early and $R^{1/4}$-like) and faint bulges (generally late and exponential-like) also emerges (e.g. Andredakis et al. 1995). A link between faint bulges and disks is even suggested and is the subject of much work (Kormendy 1993, these proceedings). All the observations discussed in this paper concern nearby galaxies, where the internal structure, kinematics, and dynamics can be studied in detail. This shows that so-called near-field cosmology has an essential (and perhaps dominant) role to play in our quest to understand galaxy formation and evolution.

Although it is impossible to be exhaustive, it is essential to discuss current instrumental developments, since they will lead without doubt to the next discoveries. The usual bells and whistles associated with "weather" prediction are however necessary. On nuclear scales, we are unlikely to make great advances from space until the advent of NGST (e.g. Stockman & Mather 2000). HST/ACS does not increase HST's spatial resolution, and HST/STIS will not be upgraded or replaced, offering few new possibilities for high spatial resolution kinematics. Adaptive optics on large ground-based telescope, particularly in the near-infrared and/or with integral-field spectrographs (IFSs), is very promising (e.g. VLT/SINFONI; Mengel et al. 2000). On intermediate scales, WHT/SAURON has already demonstrated the possibilities of wide-field IFSs, especially when supplemented with data on nuclear scales and proper modeling tools (Fig. 6; de Zeeuw et al. 2002). VLT/VIMOS and other similar instruments will increase this power. On large scales, WHT/PNS will provide much needed data on stellar kinematics in the outskirts of galaxies (using PN as tracers; see Douglas & Taylor 1999), constraining the amount of dark matter present. Astrometric missions such as ESA/GAIA (e.g. Perryman et al. 2001), acting on all scales, will provide the position, colors, type, and radial velocity for a billion stars in the Galaxy (a large fraction with accurate proper motions and parallax). This will revolutionize our view of spirals, providing us with a stereoscopic and kinematic census of the stellar populations. Near-field cosmology at its best!

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References

Andredakis, Y. C., Peletier, R. F., & Balcells, M. 1995, MNRAS, 275, 874
Athanassoula, E., & Bureau, M. 1999, ApJ, 522, 686
Bender, R., Burstein, D., & Faber, S. M. 1993, ApJ, 411, 153
Binney, J. 1976, MNRAS, 177, 19
——— 1978, MNRAS, 185, 227
Binney, J., & Petrou, M. 1985, MNRAS, 214, 449
Bureau, M., & Athanassoula, E. 1999, ApJ, 522, 686
Bureau, M., & Freeman, K. C. 1999, AJ, 118, 126
Burstein, D., Saglia, R. P., Colless, M., Davies, R. L., McMahan, R. K., & Wegner, G. 2001, in *Galaxy Disks and Disk Galaxies*, eds. J. G. Funes, S. J., & E. M. Corsini (ASP: San Francisco), 153
Byun, Y.-I., et al. 1996, AJ, 111, 1889
Capaccioli, M., Cappellaro, E., Held, E. V., & Vietri, M. 1993, A&A, 274, 69
Carollo, C. M., Ferguson, H. C., & Wyse, R. F. G. 1999, *The Formation of Galactic Bulges* (CUP: Cambridge)
Carollo, C. M., & Stiavelli, M. 1998, AJ, 115, 2306
Carollo, C. M., Stiavelli, M., & Mack, J. 1998, AJ, 116, 68
Carollo, C. M., Stiavelli, M., de Zeeuw, P. T., & Mack, J. 1997, AJ, 114, 2366
Ciotti, L. 1991, A&A, 249, 99
Combes, F., Debbasch, F., Friedli, D., & Pfenniger, D. 1990, A&A, 233, 82
Contopoulos, G., & Grøsbol, P. 1989, A&AR, 1, 261
Davies, R. L., Efstathiou, G., Fall, S. M., Illingworth, G., & Schechter, P. L. 1983, ApJ, 266, 41
Djorgovski, S., & Davis, M. 1987, ApJ, 313, 59
Douglas, N. G., & Taylor, K. 1999, MNRAS, 307, 190
Dressler, A., Lynden-Bell, D., Burstein, D., Davies, R. L., Faber, S. M., Terlevich, R., & Wegner, G. 1987, ApJ, 313, 42
Faber, S. M. 1977, in *The Evolution of Galaxies and Stellar Populations*, eds. B. M. Tinsley, & R. B. Larson (YUPS: Yale), 157
Faber, S., Dressler, A., Davies, R. L., Burstein, D., & Lynden-Bell, D. 1987, in *Nearly Normal Galaxies*, ed. S. Faber (Springer-Verlag: New York), 175
Faber, S. M., & Jackson, R. E. 1976, ApJ, 204, 668
Faber, S. M., et al. 1997, AJ, 114, 1771
Ferrarese, L., & Merritt, D. 2000, ApJ, 539, L9
Ferrarese, L., Pogge, R. W., Peterson, B. M., Merritt, D., Wandel, A., & Joseph, C. L. 2001, ApJ, 555, L79
Friedli, D., & Benz, W. 1993, A&A, 268, 65
Gebhardt, K., et al. 2000a, ApJ, 539, L13
——— 2000b, ApJ, 543, L5
Graham, A., Lauer, T. R., Colless, M., & Postman, M. 1996, ApJ, 465, 534
Heller, C. H., & Shlosman, I. 1994, ApJ, 424, 84

Hjorth, J., & Madsen, J. 1995, ApJ, 445, 55

Hui, X., Ford, H. C., Freeman, K. C., & Dopita, M. A. 1995, ApJ, 449, 592

Illingworth, G. 1977, ApJ, 218, L43

Jensen, E. B., & Thuan, T. X. 1982, ApJS, 50, 421

de Jong, R. S. 1996, A&A, 313, 45

Jørgensen, I., Franx, M., & Kjærgaard, P. 1996, MNRAS, 280, 167

Karachentsev, I. D., Karachentseva, V. E., & Parnovskij, S. L. 1993, Astronomische Nachrichten, 314, 97

Kavelaars, J. J. 1998, PASP, 110, 758

Kent, S. M. 1986, AJ, 93, 1301

King, A. R. 1966, AJ, 71, 64

Kormendy, J. 1993, in *Internal Kinematics and Dynamics of Galaxies*, ed. E. Athanassoula (Reidel: Dordrecht), 193

Kormendy, J., & Illingworth, G. 1982, ApJ, 256, 460

Kuijken, K., & Merrifield, M. R. 1995, ApJ, 443, L13

Lütticke, R., & Dettmar, R.-J. 1999, in *The Formation of Galactic Bulges*, eds. C. M. Carollo, H. C. Ferguson, & R. F. G. Wyse (CUP: Cambridge), 124

Lütticke, R., Dettmar, R.-J., & Pohlen, M. 2000, A&AS, 145, 405

Lynden-Bell, D. 1962, MNRAS, 123, 447

——— 1967, MNRAS, 136, 101

Magorrian, J., et al. 1998, AJ, 115, 2285

Mengel, S., Eisenhauer, F., Tecza, M., Thatte, N. A., Roehrle, C., Bickert, K., & Schreiber, J. 2000, Proc. SPIE, 4005, 301

Merrifield, M. R., & Kuijken, K. 1999, A&A, 345, L47

Merritt, D., & Ferrarese, L. 2001, ApJ, 547, L140

Mihos, J. C., Walker, I. R., Hernquist, L., Mendes de Oliveira, C., & Bolte, M. 1995, ApJ, 447, L87

Norman, C. A., Sellwood, J. A., & Hasan, H. 1996, ApJ, 462, 114

Ostriker, J. P., & Peebles, P. J. E. 1973, ApJ, 186, 467

Perryman, M. A. C., et al. 2001, A&A, 369, 339

Prendergast, K. H., & Tomer, E. 1970, AJ, 75, 674

Sandage, A., Freeman, K. C., & Stokes, N. R. 1970, ApJ, 160, 831

Schechter, P. L., & Gunn, J. E. 1979, ApJ, 229, 472

Seigar, M. S., & James, P. A. 1998, MNRAS, 299, 672

Sersic, J.-L. 1968, *Atlas de Galaxias Australes* (Obs. Astronomico: Cordoba)

Shaw, M. A. 1987, MNRAS, 229, 691

Silk, J., & Rees, M. J. 1998, A&A, 331, L1

Stockman, H. S., & Mather, J. C. 2000, in *Imaging the Universe in Three Dimensions*, eds. W. van Breugel, & J. Bland-Hawthorn (ASP: SF), 415

de Vaucouleurs, G. 1958, ApJ, 128, 465

Wilson, C. P. 1975, AJ, 80, 175

de Zeeuw, P. T., et al. 2002, MNRAS, 328, 513