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

Black Holes and the Central Structure of Early-type Galaxies

TOD R. LAUER
National Optical Astronomy Observatory

Abstract

Central massive black holes appear to have a strong role in determining the central structure of elliptical galaxies. The existence of cores in the more luminous ellipticals may be understood as the merger endpoint of two less-luminous galaxies, each harboring a massive black hole. As the two black holes spiral together at the center of the merger product, stars would be ejected from this region, creating a break in the stellar density profile and the shallow cusp in surface brightness characteristic of a core. Further, the resulting binary or merged black hole would preserve the core over subsequent mergers or cannibalism events by disrupting any incoming dense stellar system that would otherwise fill in the core. The effects of black holes are also strongly favored to explain central "double-nuclei," such as that seen in M31, and a recently discovered class of "hollow galaxies," which have local minima in their central stellar density profiles. In short, any discussion of the origin of galaxy morphology must include the ubiquitous presence of massive black holes.

1.1 Introduction

It is now more or less accepted that massive black holes (MBHs) are ubiquitous in the centers of galaxies (Richstone et al. 1998). Indeed, the recent work of Gebhardt et al. (2000) and Ferrarese & Merritt (2000) showing a tight relationship between the masses of black holes and the global dynamics of their hosting galaxies strongly implies that there is a deep relationship between the formation of MBHs and their associated galaxies. Once this premise is accepted, it raises the possibility that some of the characteristic morphological properties of galaxies may in fact be the frank effects of the co-formation of the galaxy with a central MBH.

The creation and preservation of "cores" in luminous elliptical galaxies appears to be one such case where the effects of MBHs on their hosting galaxies are essentially demanded. I will define cores in detail below, but briefly, they are the central region of a galaxy interior to a "break radius," r_b, at which the steep outer envelope brightness profile of the galaxy transitions to a shallow cusp. They are a phenomenon of the more massive elliptical galaxies, which are believed to be the endpoints of possibly several generations of mergers of less-luminous galaxies. A core would be generated during the merging of two galaxies as their respective central black holes spiral into the center of the merger product due to dynamical friction. The black holes form a binary system, which then hardens by ejecting stars from the center of the merged galaxy; this process creates the core structure. The binary or the ultimate merged black hole plays an additional role in preserving the core by disrupting any dense stellar systems cannibalized by the new galaxy that would otherwise fill in the core.

Black holes offer a natural explanation for some of the rarer forms of central structure seen in elliptical galaxies in addition to the more common cores. The long-term existence of "double nuclei," such as those seen in M31 (Lauer et al. 1993) and NGC 4486B (Lauer et al 1996) can only be understood as systems where a MBH dominates the central potential, allowing for long-lived and unusual distributions of stellar orbits (Tremaine 1995). Likewise a recently discovered class of "hollow galaxies" (Lauer et al. 2002), where the stellar density profile shows a local *minimum* near the galaxy center, may be cases where the formation of a core through the formation and hardening of a binary MBH has left especially obvious signatures of this mechanism. Overall, MBHs will dominate the centers of their galaxies—it indeed is quite reasonable that they will leave observable signatures in the central stellar density distributions.

1.2 The Cores of Early-type Galaxies

Traditionally, a core was defined to be a central region of a stellar system where the stellar density profile flattened out to a constant value. More specifically, convergence to the central constant value would be quadratic, so as $r \to 0$, $\rho(r) \approx \rho_0(1+\mathcal{O}r^{-2})$. Cores of this form were seen in some globular clusters—and appeared to be present in elliptical galaxies, based on photographic surface photometry. Schweitzer (1979), however, noted that seeing interacting with an extended object could create the false impression of a "well resolved" core, and questioned the conclusion that cores had been seen in elliptical galaxies. This issue was settled through the use of the then-new CCD cameras to obtain surface photometry, coupled with image processing sufficiently sophisticated to incorporate seeing into the analysis. Both Lauer (1985) and Kormendy (1985) identified several nearby giant ellipticals where the central surface brightness did appear to level off and approach a constant value. Cores did seem to be present, with "core radii," or the half-power point of the brightness profile, r_c, always less than a kiloparsec; however, Lauer (1985) noted that the detailed brightness profiles within the cores flattened out more slowly than quadratic convergence to a flat central surface brightness. At the same time, Lauer and Kormendy both emphasized that seeing did prevent cores from being observed in several, mainly low-luminosity, galaxies—these were especially interesting targets for *HST.*

Once such target was NGC 7457, which was the first galaxy observed with *HST* (Lauer et al. 1991). An extrapolation of the rough relationship between core size and luminosity observed for the galaxies resolved from the ground suggested that NGC 7457 would have a core easily detectable at *HST* resolution. Instead its brightness profile continued into the resolution limit as a steep power law [$I(r) \sim r^{-1}$]; its central stellar density was at least 10^2 higher than had been expected. *HST* observations of M32 (Lauer et al. 1992b) and M87 (Lauer et al. 1992a) also showed these galaxies to have central surface brightness cusps. The case of M87 was of particular interest; from the ground it showed a large core, but one that was strongly "non-isothermal," that is one that did not show a clear zone of constant central surface brightness. *HST* observations showed it to have a shallow cusp in surface brightness that continued unabated into its center; this was significant, as even a shallow cusp in projection implied a steep cusp in luminosity volume density—M87 appeared to have a core, but just as clearly had no extended inner region of constant density.

Subsequent observations of other galaxies with *HST* show that nearly all early-type galax-

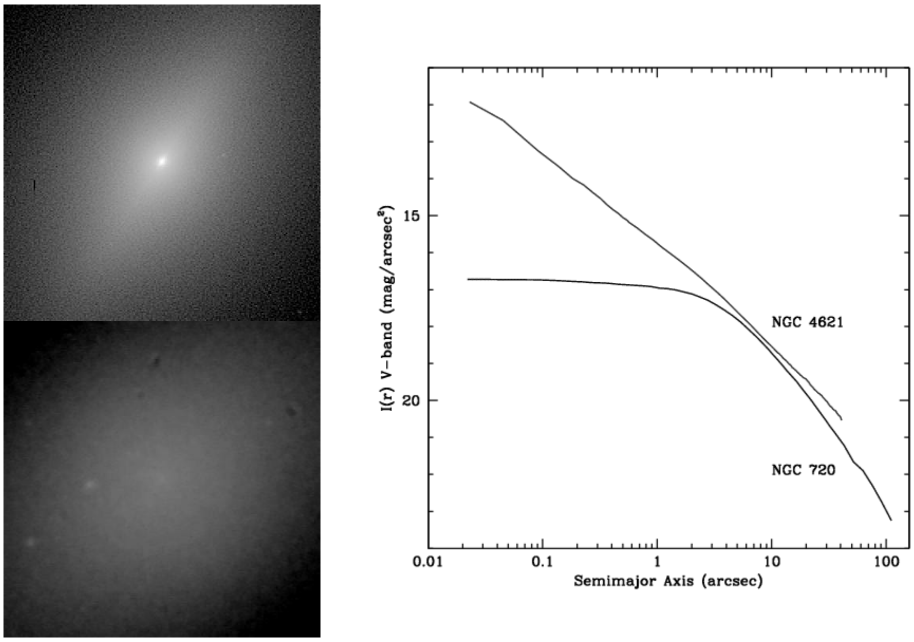

Fig. 1.1. Images and brightness profiles of the central regions of NGC 720 (bottom), a core galaxy, and NGC 4621 (top), a power-law galaxy. The galaxies have same total luminosity.

ies have central surface brightness cusps (Crane et al. 1993; Ferrarese et al. 1994; Kormendy et al. 1994; Lauer et al. 1995). None of the galaxies with "cores" seen at ground-based resolution were found to have true constant-density cores. Instead they always had shallow central cusps in surface brightness, which again always implied steep cusps in stellar density. M87, thus, was seen to be typical of galaxies that showed cores at ground-based resolution. The new observations motivated a new formal observational definition of a core as a region where the steep envelope brightness profile of a galaxy "breaks," and transitions to a shallow cusp at smaller radii of the form $I(r) \sim r^{-\gamma}$, with $0 < \gamma \leq 0.3$ (Lauer et al. 1995); a typical core galaxy is shown in Figure 1.1. The transition between the inner cusp and outer envelope is characterized by the "break-radius," r_b, which is analogous to the previous core radius, r_c, parameter; r_b is formally defined as the point of maximum logarithmic second derivative of the brightness profile. In general, r_b is roughly correlated with total galaxy luminosity and is always smaller than 1 kpc. This behavior is neatly described by the empirical "broken power-law" form below, informally known as the "Nuker Law" (Lauer et al. 1995),

$$I(r) = 2^{(\beta-\gamma)/\alpha} I_b \left(\frac{r_b}{r}\right)^{\gamma} \left[1 + \left(\frac{r}{r_b}\right)^{\alpha}\right]^{(\gamma-\beta)/\alpha}, \tag{1.1}$$

where γ is the inner power-law slope as $r \to 0$, β is the outer power-law slope as $r \to \infty$, r_b

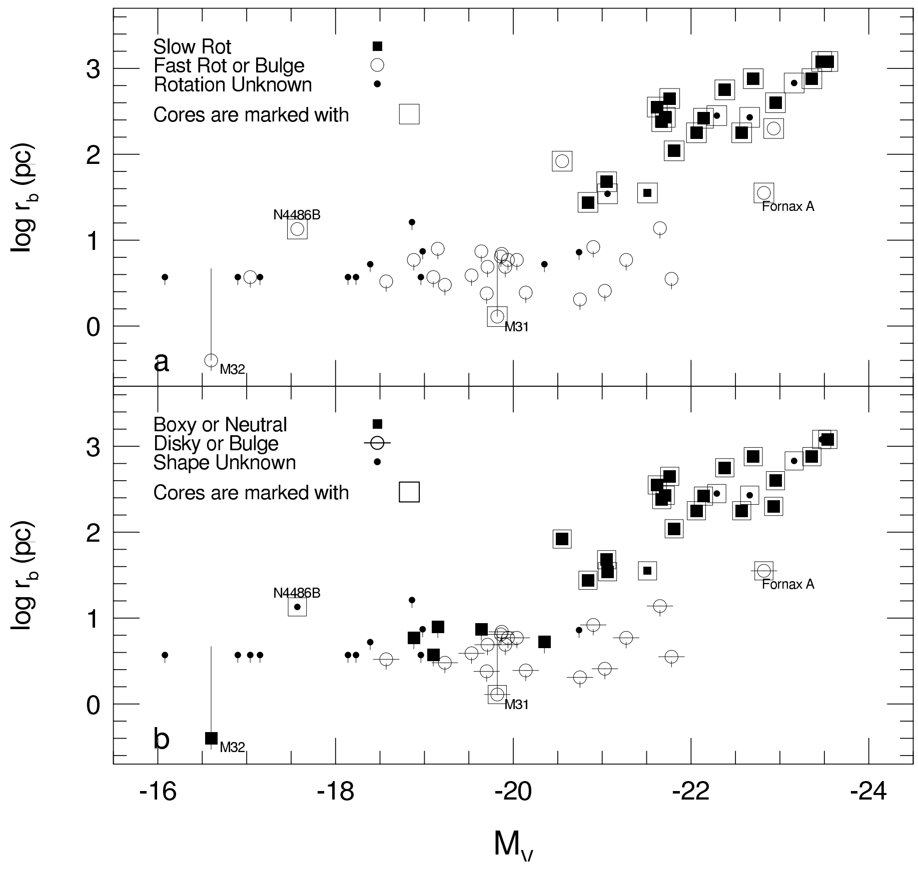

Fig. 1.2. The relationship between break radius, r_b, and total galaxy luminosity (as adopted from Faber et al. 1997). Core galaxies are indicated with an open box. Power-law galaxies are represented as upper limits on r_b. The upper panel additionally classifies the galaxies by the importance of rotation; the bottom panel classifies galaxies by isophote shape. Note that for $M_V < -20$ mag, limits on r_b for power-law galaxies fall below the core-galaxy sequence.

is the break radius, I_b is the surface brighness at the break radius, and α controls the speed of transition from the inner and outer power laws.

The key point of this revised definition of a core is that it preserves the observational schema that there are central regions of early-type galaxies where there is a physical scale at which the brightness profile becomes much shallower than the envelope, even though it abandons the more abstract idea that this transition must necessarily be associated with a central region of constant luminosity density. We do see cores, and as I will discuss shortly, their existence correlates with important properties of the galaxies in which they are seen. This is especially clear when we consider the other half of the story presented by the *HST* observations, which is the existence of galaxies in which no core is seen. Just as M87 serves as a prototype of "core" galaxies, NGC 7457 serves as an example of this second class of "power-law" galaxies.

The technical definition of a power-law galaxy is a galaxy for which no inner break in its brightness profile has been resolved; a typical example of a power-law galaxy is shown in Figure 1.1. At first glance this classification may appear to be trivial, since the detection of cores always requires some minimal angular resolution; if power-law galaxies were just core galaxies seen further away, then this definition would be of little use. The power-law classification was motivated instead by the existence of galaxies observed at the same resolution and distance as core galaxies that instead had brightness profiles that continued into the *HST* resolution as steep power-law cusps, or $I(r) \sim r^{-\gamma}$, with $\gamma > 0.5$. These galaxies generally were lower luminosity systems that had no cores detectable at ground-based resolution that now had limits of $r_b < 10$ pc at *HST* resolution. Since r_b for core galaxies roughly correlates with luminosity, it might be assumed for some of the power-law galaxies would have cores appropriate for their luminosity, but which escaped even *HST* resolution. The power-law classification was most interesting, however, for those galaxies that had limits on r_b well below those of core galaxies of the same total luminosity at the same distance. Absence of a core for such systems is thus physically important. It may be that some power-law galaxies may ultimately reveal cores at the few parsec scale or finer when observations that surpass *HST* resolution become available, but there is no reason to presume that this will be the case. Furthermore, the scale of such cores will be discontinuous with the r_b vs. luminosity relationship for core galaxies.

Presence or absence of a core is related to other properties of the galaxies (Faber et al. 1997). Figure 1.2 shows the relationship between core size, as quantified by r_b, and total luminosity. For the most part, core galaxies have $M_V < -21$ mag; for these galaxies $r_b \sim L^{1.2}$, but with significant scatter. Power-law galaxies, as noted above, are in general less luminous, but can be as bright as $M_V \approx -22$ mag. Limits on r_b for power-law galaxies with $M_V < -20$ mag fall well below the r_b vs. L relationship for core galaxies of the same luminosity.

Faber et al. (1997) strongly argue that power-law and core galaxies define two distinct classes of central structure in early-type galaxies. Nearly all early-type galaxies have singular stellar density profiles, but the structural properties of the two types are not continuous. While core galaxies always have $0 < \gamma \leq 0.3$, power-law galaxies always have $\gamma > 0.5$— there is a clear gap between the two structural forms and the distribution of inner cusp slopes is bimodal. This is especially vivid in the comparison of stellar density profiles of both types presented by Gebhardt et al. (1996) shown in Figure 1.3. Recently, Ravindranath et al. (2001) and Rest et al. (2001), who both have studied much larger galaxy samples with *HST,* have identified a few systems with intermediate cusp slopes that fall between the core and power-law division; however, such systems are relatively uncommon, and the overall bimodal distribution in central properties appears to be robust (see Fig. 1.4).

The division of early-type galaxies into core and power-laws is really underscored when the dynamical and morphological properties of the two types are compared (Faber et al. 1997). Core galaxies are slow rotators and have boxy isophotes, while power-law galaxies are marked by rapid rotation and disky isophotes. These differences indeed are especially evident when comparing power-law and core galaxies of the same luminosity. Luminosity is removed as a discriminate, but the galaxies' dynamic and morphological states still match up neatly with the ones that have cores and the ones that do not. These differences plus

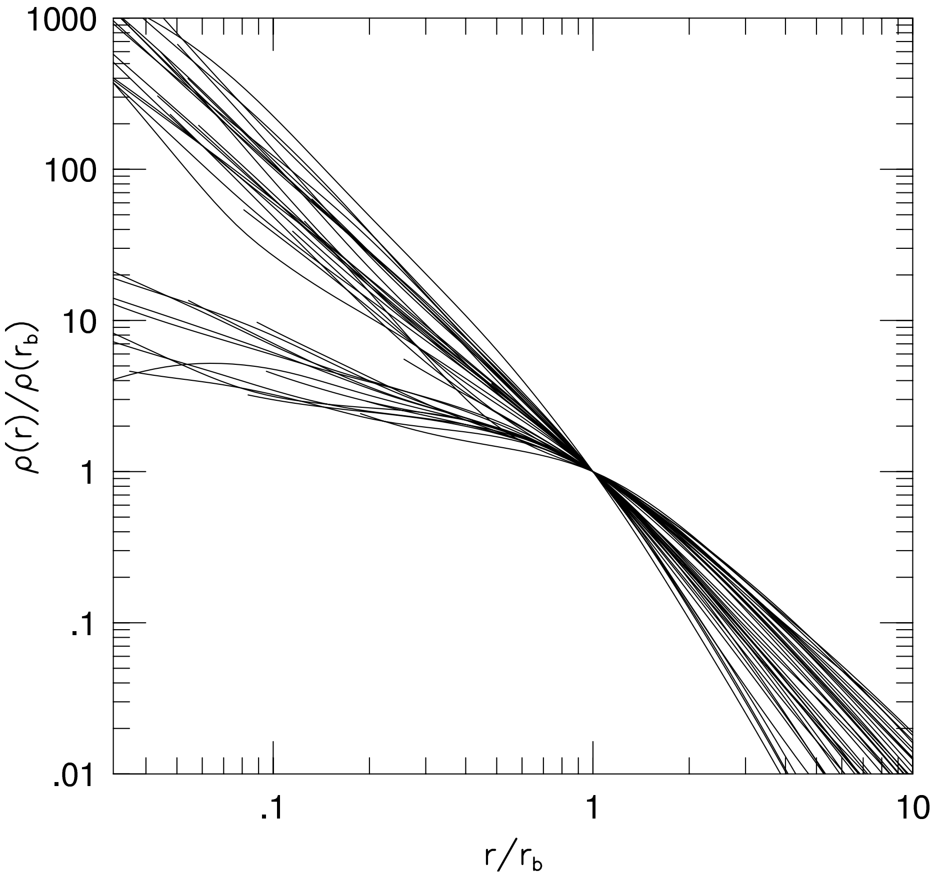

Fig. 1.3. Stellar luminosity density profiles are plotted, showing the dichotomy between core and power-law galaxies. The radial scale is normalized by the break radius; for power-law galaxies, this is taken in this context as the point of maximum logarithmic second derivative in their brightness profile. (Figure adapted from Gebhardt et al. 1996.)

the overall high luminosities of core galaxies strongly suggest the role of galaxy mergers in creating the core galaxies.

The absence of cores in power-law galaxies is especially important when we compare the stellar *volume density* profiles of core and power-law galaxies. Although both types of galaxies have singular density profiles into the resolution limit, the greatly steeper slopes of the power-law galaxy density profiles means that for $r < 100$ pc these galaxies may have stellar densities that exceed those of core galaxies by several orders of magnitude. As outlined in the next section, this is critically important for understanding the formation of central structure in the context of galaxy formation overall.

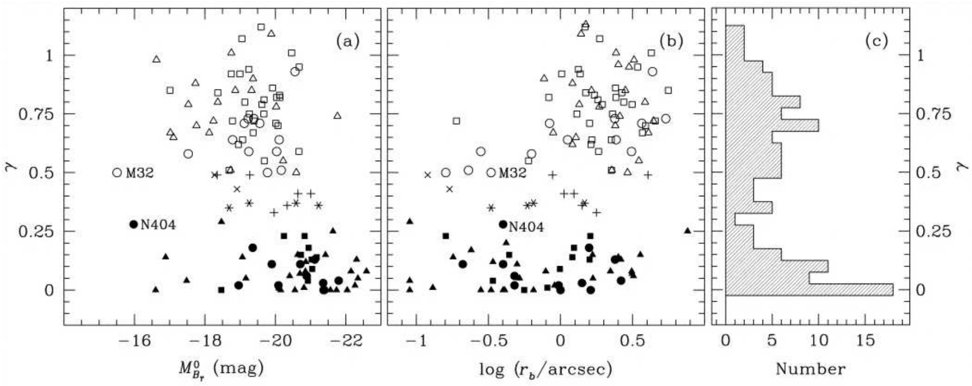

Fig. 1.4. The complete compendium of central cusp slopes as presented in Ravindranath et al. (2001). Dependence of the inner cusp slope on (a) absolute magnitude of the galaxy ($M^0_{B_T}$) and (b) break radius (r_b), showing core galaxies (filled symbols) and power-law galaxies (open symbols). The circles denote the galaxies from Ravindranath et al. (2001), triangles those from Faber et al. (1997), and squares those from Rest et al. (2001). Objects in the sample of Ravindranath et al. that fall in the gap region ($0.3 < \gamma < 0.5$) appear as asterisks, while those from Rest et al. (2001) are shown by plus signs. Two galaxies that fall in this region from Faber et al. (1997) are shown by crosses. (c) Distribution of γ.

1.3 Core Formation and Black Holes

All modern galaxy formation scenarios imply that the most luminous galaxies are the endpoints of a merging hierarchy of less luminous systems. That cores for the most part only appear in the more luminous, nonrotating, and boxy early-type galaxies strongly suggests that cores are not created during the first generation of galaxy formation but arise from mergers at later epochs. Begelman, Blandford, & Rees (1980) were the first to present a specific scenario under which this might happen. Begelman et al. were concerned with the merging of two galaxies, each harboring a central MBH. As the merger progressed the two black holes would sink by dynamical friction into the common center of the merger remnant, creating a binary MBH. Subsequent three-body interactions between the binary and surrounding stars would eject stars from the center of the galaxy and harden the binary. Roughly speaking, a mass exchange would take place at the center of the merger remnant. Coalescence of the binary MBH displaces a similar mass of star, producing a core. Intriguingly, Begelman et al. suggested that enough stars might be ejected from the center that the stellar density profile might actually have a local minimum in the very center. In any case, the density profile would exhibit an abrupt decrease in slope as the center was approached; in projection this would create the appearance of a core.

The Begelman et al. (1980) discussion predated both a general picture of the central structure of early-type galaxies as well as an understanding of the prevalence of MBHs in galaxy centers. More recent work has looked at the creation of cores in the general context of galaxy mergers and again showed that the end state of the merger of two galaxies both with central MBHs created cores. Ebisuzaki, Makino, & Okumura (1991), Makino (1997), and Quinlan (1997) all used *N*-body simulations of sufficient resolution to elucidate the central structure of mergers produced in this scenario. Ebisuzaki et al. (1991), for example, showed that the core created in the remnant would have a shallow cusp in the density profile, consistent with the *HST* observations that shortly followed after this study.

Milosavljević & Merritt (2001) have recently presented simulations of galaxy mergers with MBHs that have been informed by the modern picture of central galaxy structure provided by *HST* observations. Their starting point is two galaxies with structure appropriate for power-law galaxies. As a MBH binary is created in the merger and hardens, a break appears in the stellar volume profile. The profile interior to the break retains the form of a power law in radius, but with shallower slope than the envelope outside the break. Projection of the merger product not only features a system with a core, but one that has an interior surface brightness cusp, in excellent agreement with the modern picture of core galaxies.

While all the theoretical work quoted above strongly suggests that the creation of a binary black hole in a merger will create a core in the merger remnant, it is mute on the importance of this process for creating cores overall. It is not sufficient just to create a core, however; it must survive until the present epoch against any number of subsequent mechanisms that would deliver gas and stars into central potential of the merged system. That cores have indeed survived over time is the final piece of the puzzle that essentially demands that cores in early-type systems are uniquely tied to MBHs.

The problem of core survival can be understood by considering the existence of cores in the highly luminous brightest cluster galaxies (BCGs), nearly all of which are seen to have cores (Laine et al. 2003). Even if the BCGs were largely created at early times, they continue to cannibalize less luminous cluster galaxies at a significant rate at the present epoch (Merritt 1985; Lauer 1988). Although a modest cannibalism rate may have little effect on the overall structure of these galaxies, this is less true in their centers. The low-luminosity power-law galaxies will be just the systems cannibalized by the BCG, but their high central stellar densities strongly suggest that their central portions should survive partially intact into the cores of the BCGs. In short, how do cores avoid being filled in by cannibalized remnants?

The prevalence of cores at this epoch was raised by Faber et al. (1997) as a strong argument that there must be some disruptive mechanism or guardian that preserves the cores of luminous galaxies over the infall of cannibalized systems. Considering the 14 brightest galaxies in the Lauer et al. (1995) sample, seven of which were BCGs, even a modest cannibalism rate of $0.2L^{*}$ Gyr^{-1} (Lauer 1988) predicts that *each* of these galaxies should have cannibalized two systems since $z \approx 1$. Given the strong central density contrast, $> 10^{3}$, between the typical power-law elliptical and BCG, simple tidal arguments suggest that the centers of the power-law galaxies should fall undisrupted into the centers of the BCGs. Kormendy (1984) contemplated this possibility in advance of *HST* observations, suggesting that some luminous galaxies would be found to have a "core within a core"; such systems, however, have never been seen. This scenario was tested in detail by Holley-Bockelmann & Richstone (1999) with *N*-body simulations. If a luminous galaxy *without* a central MBH cannibalizes a less luminous system, above some luminosity difference, the less luminous galaxy will on average be dense enough at its center to survive central accretion into the more massive system. Stripping and tidal disruption of the envelope of the infalling less luminous galaxy will indeed take place, but its nucleus, itself, will indeed settle down unscathed within the core of the massive galaxy.

The hypothesis is that cores, once created, are protected against being filled in by subsequent mergers by the resident MBH acting as a "guardian." The strong tidal forces of an MBH would disrupt any dense stellar system approaching the nucleus. If the incoming nucleus itself contained an MBH, the subsequent formation and hardening of an MBH binary would serve the same purpose.

Again this scenario has been born out by the simulations of Holley-Bockelmann & Richstone (2000), in which they studied the accretion of galaxies with power-law density profiles by more luminous galaxies harboring central MBHs. The strong tidal fields associated with the MBH of typical mass expected based on the Gebhardt et al. (2000) and Ferrarese & Merritt (2000) relationships were more than sufficient to disrupt the power-law galaxies. In short, black holes can serve as a guardian of cores over cannibalism events; there are no viable alternative hypotheses for preserving cores from the accretion of the nuclei of less-luminous galaxies.

One potentially interesting "loose end" to this picture are the small handful of BCGs that have anomalously small cores or steep power-law cusps into the *HST* resolution limit. Faber et al. (1997) identified NGC 1316 (Fornax A) as a galaxy of high luminous with a compact core falling well below the Faber et al. r_b vs. L relationship. Laine et al. (2003) identified three BGCs of similar high luminosity with cores or upper limits on r_b over an order of magnitude smaller than the mean r_b seen at their luminosities. Since the most massive galaxies may under go several generations of mergers or cannibalism, once speculation may be that cores were initially created in these systems, but somehow their MBH were thwarted as guardians later on. One possibility is that the binary MBH created in on merger was ejected in a relativistic three-body interaction with a third MBH introduced by a later cannibalism event. Still later events could fill in the unprotected cores, perhaps also reintroducing MBH of masses more appropriate to the incoming low-luminosity systems. If so the MBH in NGC 1316 that powers its activity may fall below the predictions of the Gebhardt et al. (2000) and Ferrarese & Merritt (2000) relationships.

1.4 Double Nuclei and Hollow Galaxies

The definition of a core given above is entirely in terms of the projected brightness profile and its implicit reflection of the more fundamental stellar density profile. For most core galaxies this is sufficient—the full morphological appearance of the core is completely encapsulated by the one-dimensional density profile, modulo smooth changes in the isophote ellipticity shape or orientation. There is a small handful of systems, however, that have more interesting core structures that may provide unique testimony to the role of black holes in shaping central galaxy structure.

The bare existence of the double nucleus of M31 (Lauer et al. 1993, 1998) initially posed several difficulties. The small, few-parsec separation of the two nuclear components could endure only for an exceptionally short time, yet there was no additional evidence of any recent cannibalism by the M31 bulge. Tremaine (1995) resolved this difficulty by proposing that the bright P1 M31 nuclear component was not a compact star cluster falling into the nucleus, but was rather the projection of stars lingering at the apocenter of an eccentric disk of stars orbiting the $3 \times 10^7 M_\odot$ MBH believed to exist at the center of M31 (Kormendy & Bender 1999). The M31 MBH is thus essentially required as the only mechanism that allows the M31 double nucleus to exist for astronomically long time scales. Identification of NGC 4486B as a second double nucleus system (Lauer et al. 1996), together with the evidence for an especially massive black hole at the center of this system (Kormendy et al. 1997) bolsters, this picture.

Recently, Lauer et al. (2002) identified a handful of core galaxies that had stellar densities

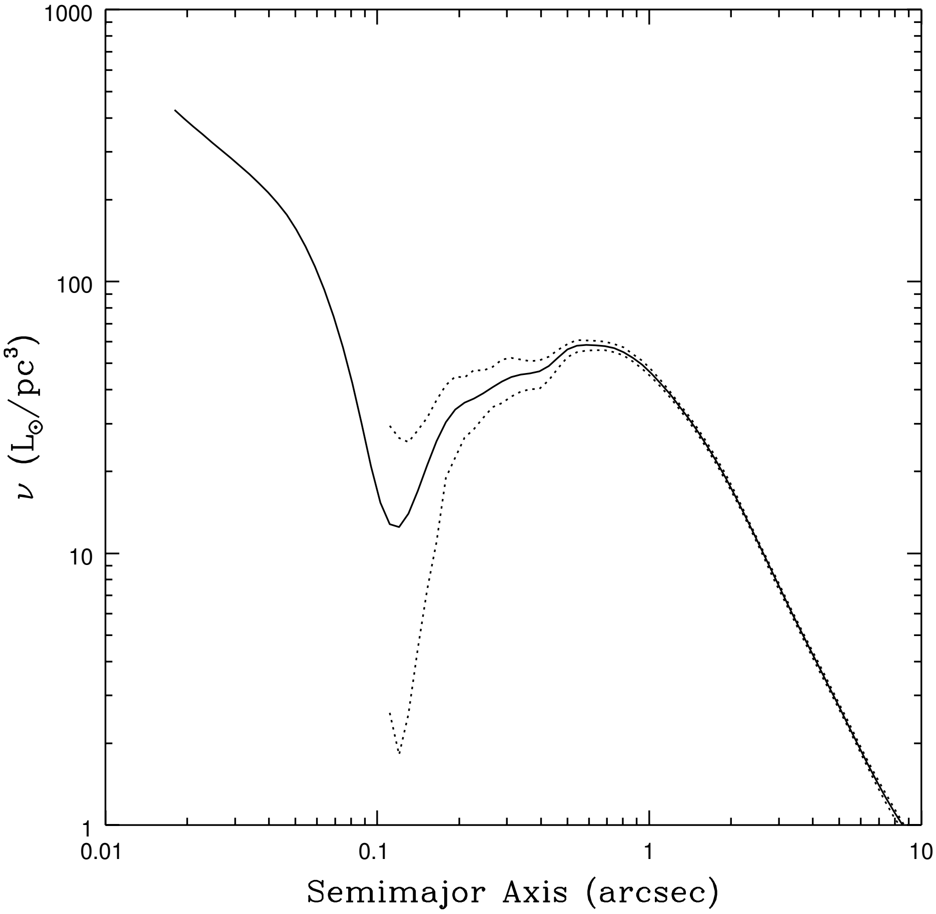

Fig. 1.5. The stellar luminosity density profile for the Virgo elliptical galaxy NGC 4406 is shown. Note the *decrease* in luminosity density interior to one arcsecond. The ultimate central rise appears to be associated with an unresolved compact nuclear source. The bracketing lines give the $1\,\sigma$ error estimates on the profile.

that actually *decreased* at small radii ($r \ll 100$ pc) moving in toward the galaxy center; an example is shown in Figure 1.5. These systems thus had local *minima* in density interior to their break radii; in a sense their cores could be considered to be partially "hollowed out." These systems may be particularly interesting test cases of the formation of cores by the intercession of MBH binaries. Lauer et al. (2002) advanced two complimentary interpretations of the hollow cores. In one scenario the cores more or less retain a normal stellar density profile, but a diffuse torus of stars has been introduced to the core, creating a local density maximum at the radii it would dominate a normal "background" radial density profile; the local density minimum is thus an illusion generated by the addition of the torus. The *N*-body simulations of Holley-Bockelmann & Richstone (2000) and Zier & Biermann

(2001) indeed show that diffuse stellar tori can be created in a merger as the centers of the two merging galaxies are disrupted by the tidal fields associated with the binary MBH created in the merger.

The second scenario proposed by Lauer et al. (2002) is that the hardening of the binary MBH within the merged core actually is effective enough at transferring energy to stars initially within the core that they are ejected to much larger radii, such that the core really is partially evacuated. As noted above, Begelman et al. (1980) suggested that this mechanism could occur as a binary MBH would harden. The simulations of Makino (1997) indeed appear to show the evacuation of cores in some cases. Comparing the Makino simulations against those of Milosavljević & Merritt (2001), which did not show evacuated cores, raises the possibility that core evacuation depends on the density profiles of the progenitor galaxies. Milosavljević & Merritt merged only power-law galaxies, while Makino merged systems that had pre-existing cores. The binary MBH ejects stars from the center in both cases, but real evacuation of the final merged core is only evident when the initial systems are not very centrally dense in stars to begin with.

1.5 Desiderata

The case that cores are a signature of black holes can be succinctly summarized as follows. *N*-body simulations show that cores can be created in the merger of two galaxies, each possessing its own MBH. The preservation of cores since the epoch of galaxy formation additionally requires MBHs to serve as guardians against destruction of the core by later infall of dense stellar systems. Within this simple picture, however, there remains more work to be done, some of which I outline below.

What are the real starting conditions for building galaxy centers? The discovery of QSOs at $z > 6$ makes it clear the MBHs were forming just as galaxy formation was getting started. Understanding how the construction of galactic nuclei progressed is closely tied to understanding the initial mass function of MBHs plus the properties of the initial stellar systems within which they presumably formed.

How does the onset of core formation fit within the complete context of hierarchical galaxy formation? If cores are formed in mergers, we still have the problem of why they appear so suddenly at $M_V < -21$ mag. Power-law galaxies would have been built in a merging hierarchy as well and also have central MBH. How do they avoid getting cores? Faber et al. (1997) argued that for lower-luminosity systems infall of gas and associated dissipative processes and star formation would have remained important. A complete picture of galaxy formation needs to cleanly explain the transition of power-law to core forms as luminosity increases.

How does the detailed core structure arise? Within the class of core galaxies, systems have diverse inner cusp slopes, a significant spread in core size at any given luminosity, and so on. Are these details interesting diagnostics of the construction history of galaxies?

What other things can massive black holes do to core structure? The notion that creation of an MBH binary is tied to core formation raises any number of issues. As discussed above, interaction of the binary with new MBHs delivered to the nucleus may ultimately cause ejection of all MBHs from the core. The binary may wander within the core at some level. Both of these may have structural implications. Lastly, the central MBH may grow significantly due to central gas accretion. Does the core structure evolve adiabatically as this occurs, the presumption underlying some of the classic inquiries into the effects of MBH on core structure (Young et al. 1978)?

Acknowledgements. I conclude by thanking my collaborators on the Nuker team: Doug Richstone (PI), Ralf Bender, Gary Bower, Alan Dressler, Sandy Faber, Alex Filippenko, Karl Gebhardt, Richard Green, Carl Grillmair, Luis Ho, John Kormendy, John Magorrian, Jason Pinkney, and Scott Tremaine. It has been a pleasure working with them to have at least gotten this far!

References

Begelman, M. C., Blandford, R. D., & Rees, M. J. 1980, Nature, 287, 307
Crane, P., et al. 1993, AJ, 106, 1371
Ebisuzaki, T., Makino, J., & Okumura, S. K. 1991, Nature, 354, 212
Faber, S. M., et al. 1997, AJ, 114, 1771
Ferrarese, L., & Merritt, D. 2000. ApJ, 539, L9
Ferrarese, L., van den Bosch, F. C., Ford, H. C., Jaffe, W., & O'Connell, R. W. 1994, AJ, 108, 1598
Gebhardt, K., et al. 1996, AJ, 112, 105
——. 2000, ApJ, 539, L13
Holley-Bockelmann, K., & Richstone, D. O. 1999, ApJ, 517, 92
——. 2000, ApJ, 531, 232
Kormendy, J. 1984, ApJ, 287, 577
——. 1985, ApJ, 292, L9
Kormendy, J., et al. 1997, ApJ, 473, L91
Kormendy, J., & Bender, R. 1999, ApJ, 522, 772
Kormendy, J., Dressler, A., Byun, Y.-I., Faber, S. M., Grillmair, C., Lauer, T. R., Richstone, D., & Tremaine, S. 1994, in ESO/OHP Workshop on Dwarf Galaxies, ed. G. Meylan & Ph. Prugniel (Garching: ESO), 147
Laine, S., Lauer, T. R., van der Marel, R. P., & Postman, M. 2003, AJ, 125, 478
Lauer, T. R. 1985, ApJ, 292, 104
——. 1988, ApJ, 325, 49
Lauer, T. R., et al. 1991, ApJ, 369, L41
——. 1992a, AJ, 103, 703
——. 1992b, AJ, 104, 552
——. 1993, AJ, 106, 1436
——. 1995, AJ, 110, 2622
——. 1996, ApJ, 471, L79
——. 2002, AJ, 124, 1975
Lauer, T. R., Faber, S. M., Ajhar, E. A., Grillmair, C. J., & Scowen, P. A. 1998, AJ, 116, 2263
Makino, J. 1997, ApJ, 478, 58
Merritt, D. 1985, ApJ, 289, 18
Milosavljević, M., & Merritt, D. 2001, ApJ, 563, 34
Quinlan, G. D. 1997, NewA, 1, 35
Ravindranath, S., Ho, L. C., Peng, C. Y., Filippenko, A. V., & Sargent, W. L. W. 2001, AJ, 122, 653
Rest, A., van den Bosch, F. C., Jaffe, W., Tran, H., Tsvetanov, Z., Ford, H. C., Davies, J., & Schafer, J. 2001, AJ, 121, 2431
Richstone, D., et al. 1998, Nature, 395, A14
Schweizer, F. 1979, 233, 23
Tremaine, S. 1995, AJ, 110, 628
Young, P. J., Westphal, J. A., Kristian, J., Wilson, C. P., & Landauer, F. P. 1978, ApJ, 221, 721
Zier, C., & Biermann, P. L. 2001, A&A, 377, 23