The Central Structure of Elliptical Galaxies and the Stellar-Dynamical Search for Supermassive Black Holes

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Abstract. **Elliptical galaxies** are divided into two types: galaxies with steep profiles that show no breaks in slope or that have extra light at small radii compared to a Sérsic function fit and galaxies that show a break from steep outer profiles to shallow inner profiles. These *cuspy cores* are important because they are a sign of undiscovered physical processes. Profiles with extra light near the center resemble predictions of starburst remnants formed in dissipative mergers. There is growing evidence for a dichotomy between (1) normal- and low-luminosity Es that rotate rapidly, that are nearly isotropic, oblate-spheroidal, and substantially flattened, that have disky-distorted isophotes, and that are *coreless*, and (2) giant Es that are essentially nonrotating, that are anisotropic, modestly triaxial, and not very flattened, that are boxy-distorted, and that have *cuspy cores*.
Black hole (BH) search: *Hubble Space Telescope* (HST) observations confirm ground-based BH detections and show that mass measurements are remarkably robust. Detection of large proper motions near the Galactic center make it one of the best BH cases. Demographic results include the discovery of enough BH mass to account for quasar energetics and strong evidence that BH mass correlates with bulge luminosity.
M 31 nucleus: New CFHT spectroscopy supports Tremaine's model that both nuclei are part of an eccentric disk of stars orbiting the BH. The BH is offset from the center of mass, confirming that $M_\bullet \simeq 3\times10^7$ $M_\odot$.

1. Elliptical Galaxies

This section discusses three subjects, (1.1) the existence and importance of cuspy cores, (1.2) coreless galaxies: some of these show "excess" starlight near their centers as in Mihos & Hernquist's (1994) models of starbursts made by dissipative mergers, and (1.3) the observation that there are two kinds of elliptical galaxies with different physical properties; these include the presence or absence of a core. Sections 1.1 and 1.3 are largely review; § 1.2 is new here.

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1.1. Cuspy Cores

HST has revolutionized the study of cores, providing enough resolution to reveal the density distribution well inside the "core radius" in the best cases. Sections 1.1 – 1.3 provide a brief review. But review is not my main purpose. I want to demonstrate a point that has become somewhat controversial, namely that the concept of a core is still physically meaningful.

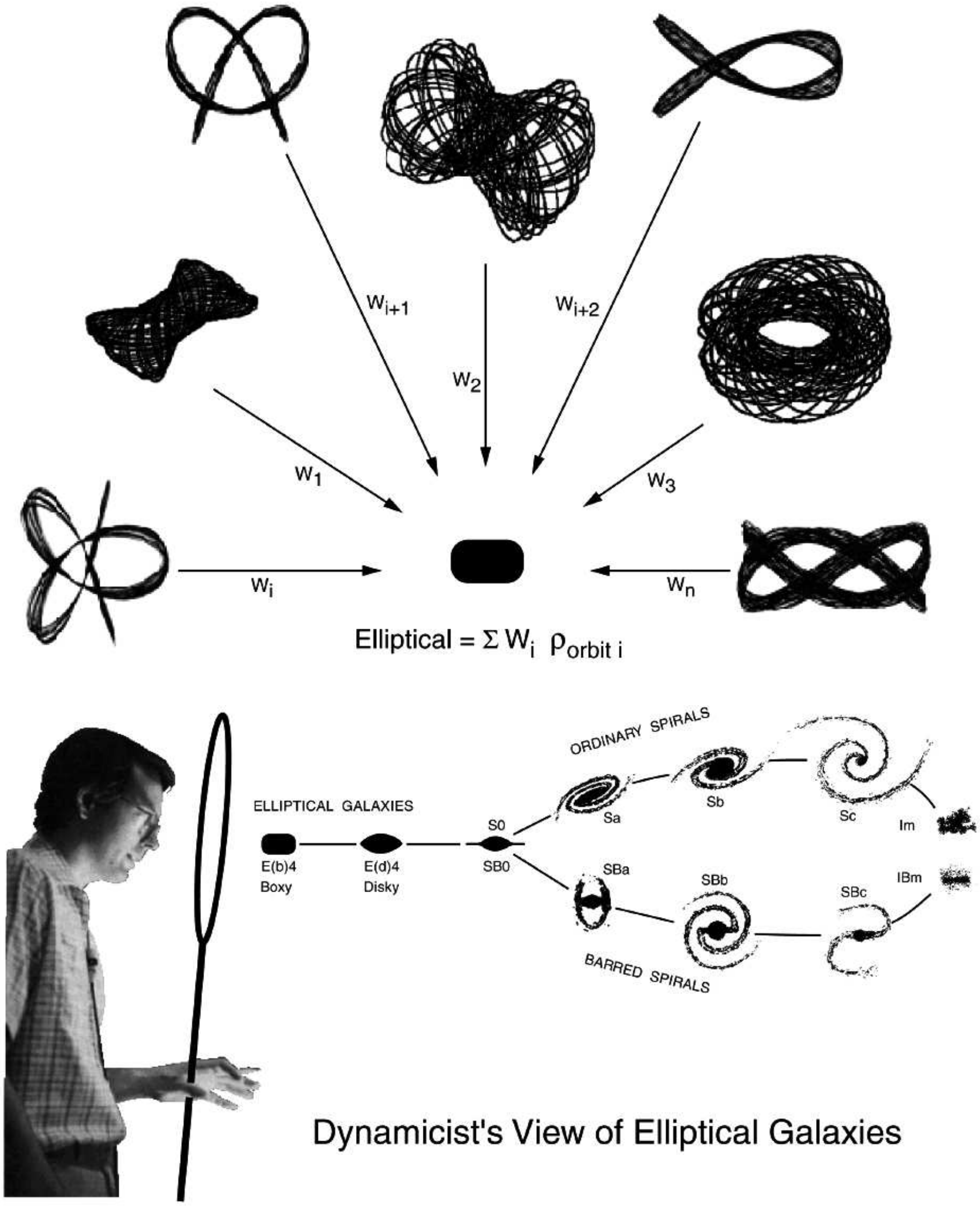

Figure 1. Dynamicists see an elliptical as a sum of the density distributions corresponding to orbits of various kinds, each weighted by the relative number of stars W_i that populate it. Of course, this is an oversimplification: they are also interested in processes of formation and evolution.

The controversy is rooted in part in the different ways that dynamicists and observers tend to see ellipticals (Figure 1, 2). Both points of view are correct, but they tend to make people ask different scientific questions, so different observational results are important to the two groups.

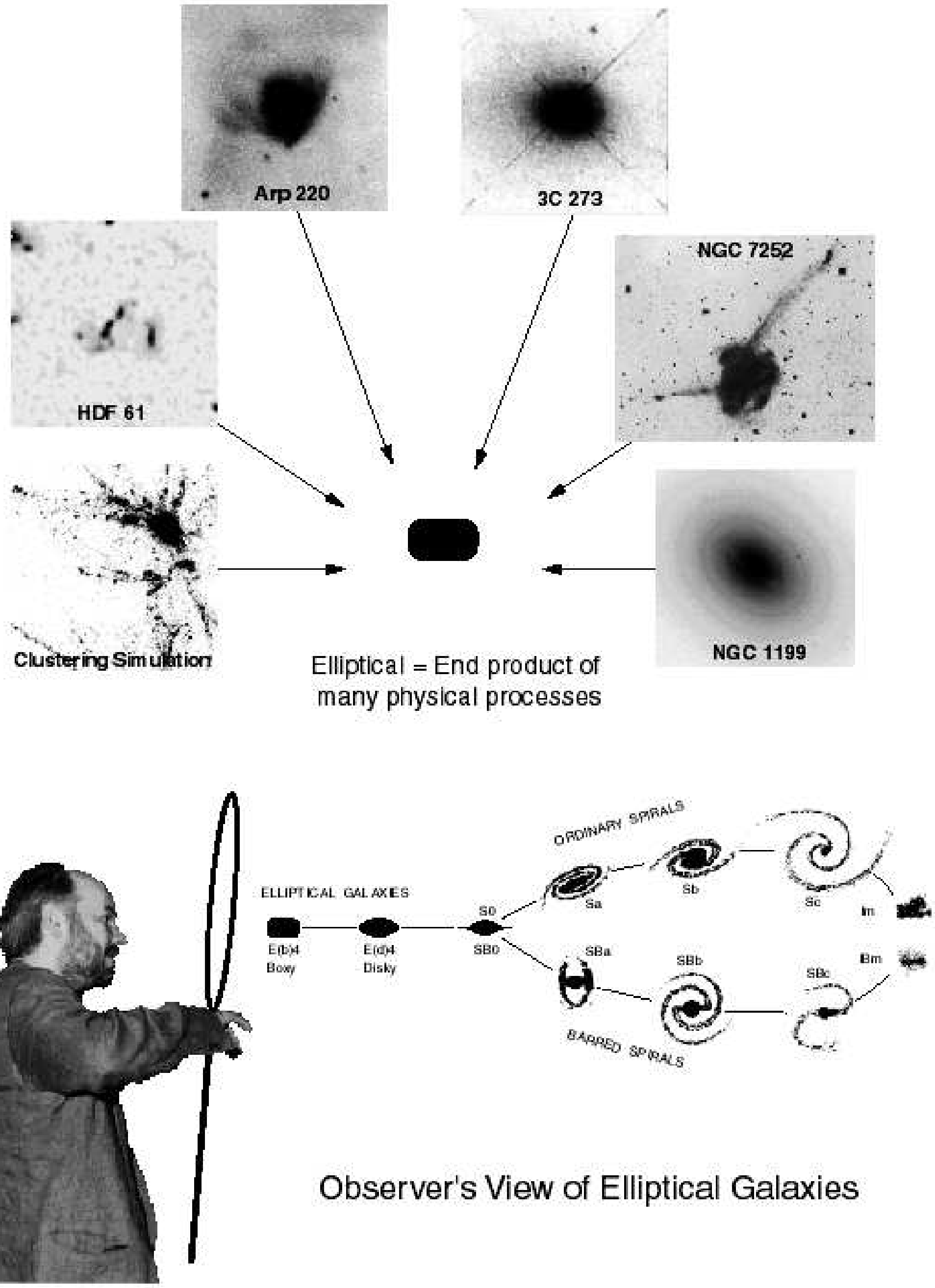

Figure 2. Observers see an elliptical as the result of physical processes of formation and evolution. Again, this is an oversimplification: they are also interested in orbit families and their populations.

Cores have been studied for many years (Kormendy 1987a gives a review). In the photographic era, it appeared that surface brightness Σ converges to a constant value as radius $r \to 0$. Because similar behavior was observed in globular clusters and because flat cores have special properties (Tremaine 1997), $\Sigma \to$ constant became associated with the concept of a core. The issue now is that for some dynamicists, this is still true, and any profile that does not have constant density at the center cannot have a core (e. g., Dehnen 1993; Merritt & Valluri 1996; Merritt & Fridman 1996; Merritt 1997). The physics that results from cuspy density profiles is not in dispute, so the issue of whether or not to use the term "core" may seem purely semantic. But other physics is at stake. Therefore I argue in this section that (cuspy) cores exist and deserve study.

CCDs showed that early signs of non-constant central Σ (King 1978) were correct: Young *et al.* (1978), Lauer (1985a, b) and Kormendy (1985a, 1987a) found that core densities do not flatten completely as $r \to 0$. Meanwhile, many physical results had been derived about cores, including "fundamental plane" (FP) parameter correlations (Kormendy 1984; Lauer 1985a, b; Kormendy 1985b) and the realization from these that elliptical and dwarf spheroidal galaxies are physically unrelated (Kormendy 1985b, 1987b). These results remain valid.

HST shows that profiles have non-zero slope at least to $r \simeq 0''.1$. The new paradigm for "cuspy cores" is this: the inner profile is a shallow power law out to a break radius r_b where it gradually changes to a steep outer profile (Lauer *et al.* 1992; Crane *et al.* 1993; Kormendy *et nuk.* 1994; Ferrarese *et al.* 1994; Forbes *et al.* 1995; Lauer *et nuk.* 1995; Byun *et nuk.* 1996; Faber *et nuk.* 1997). As emphasized by Lauer *et al.* (1992), Merritt (1993), Merritt & Fridman (1995), Kormendy *et nuk.* (1996), and Gebhardt *et nuk.* (1996), even core galaxies have shallow power-law cusps in their central volume density distributions. Ground-based measurements of core parameters are closely related to r_b and $I_b \equiv I(r_b)$ (Kormendy *et nuk.* 1994). So we have been studying the same physics all along.

A major surprise revealed by HST is that cores are found only in ellipticals with absolute magnitude $M_B \lesssim -20.5$ (Hubble constant $H_0 = 80$ km s^{-1} Mpc^{-1}). Low-luminosity ellipticals do not show the break in profile slope that implies a core. I follow Nuker team practice and call these "power-law" galaxies. The inner slope of the projected profile, $\gamma = -d \ln \Sigma / d \ln r$ is bimodal: $\gamma \simeq 0.1 \pm 0.1$ for core galaxies and $\gtrsim 0.5$ for power-law galaxies (Kormendy *et nuk.* 1994; Gebhardt *et nuk.* 1996; Faber *et nuk.* 1997). Core and power-law galaxies overlap in luminosity. But there is a qualitative dichotomy in profile shapes.

A dynamicist who focuses on orbit families and their populations may have a different emphasis. Central deprojected density profiles are cuspy in almost all ellipticals; the difference between core and power-law galaxies is merely one of degree. If one's main interest is, e. g., chaotic mixing and the consequent evolution from mildly triaxial to nearly axisymmetric shapes (Merritt 1997, 1998; Valluri & Merritt 1998, and references therein), then the same processes happen in core and power-law galaxies, they just happen at different rates.

Moreover, Merritt (1994, 1997) and Dehnen (1993) have emphasized that for small γ, the projected profiles are almost degenerate in the sense that nearly identical projected profiles can imply unprojected profiles with substantially different slopes (Figure 3). Even if projected "cores" seem to have a nearly universal shape, the volume density profiles can vary widely.

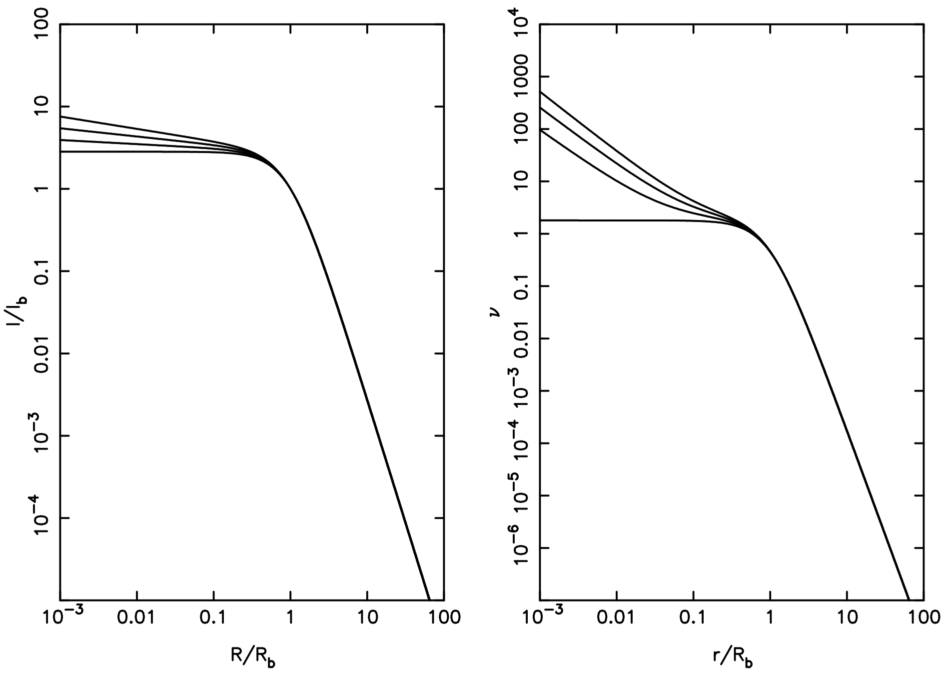

Figure 3. Projected (*left*) and unprojected (*right*) "Nuker laws" (Lauer *et nuk.* 1995, Equation 3) with similar $\gamma = 0.0,\ 0.05,\ 0.1,\ 0.15$ (bottom to top at small radii) and $\beta = 3$. This figure is provided by Merritt (1994).

So, Merritt (1994, 1997) and Merritt & Fridman (1996) state that cores do not exist at all – that the apparent cores are a misleading result of projection.

The trouble with this point of view is that it puts all of the emphasis on the inner profile slope and none on the fact that we observe (even in Fig. 3) a well defined break in slope at a well defined radius r_b. We will see that r_b and I_b correlate with other physical properties. This is a sign that they are controlled by interesting physical processes. This physics is ignored if cores are ignored.

The reason for this lengthy preamble is that, when a difference of opinion happens, it is important to understand why. In some cases, it is not produced by an error on either side, but rather by incommensurate paradigms – by different ways of looking at a problem. In the words of Kuhn (1970), "people talk past each other". This seems to be the situation here. In an attempt to integrate both points of view, I turn next to the evidence that cores exist (this section) and that they are physically important (§ 1.3). On the way, I will make a detour into the properties of power-law galaxies (§ 1.2), because they contain a new result that is interesting on its own and that may help us to understand cores.

A limitation of previous Nuker work is that we illustrated profiles over a small radius range, usually from $\sim 0\farcs01$ to $\sim 10''$. Gebhardt *et nuk.* (1996) illustrate deprojected profiles for 42 early-type galaxies observed with HST to show that they divide into core and power-law galaxies. However, all of the profiles are somewhat curved in log–log coordinates. Since only a limited radius range is shown, it is reasonable to wonder whether the difference between core and power-law galaxies is fundamental or just a matter of degree. I address this issue here by constructing composite profiles that reach much larger radii.

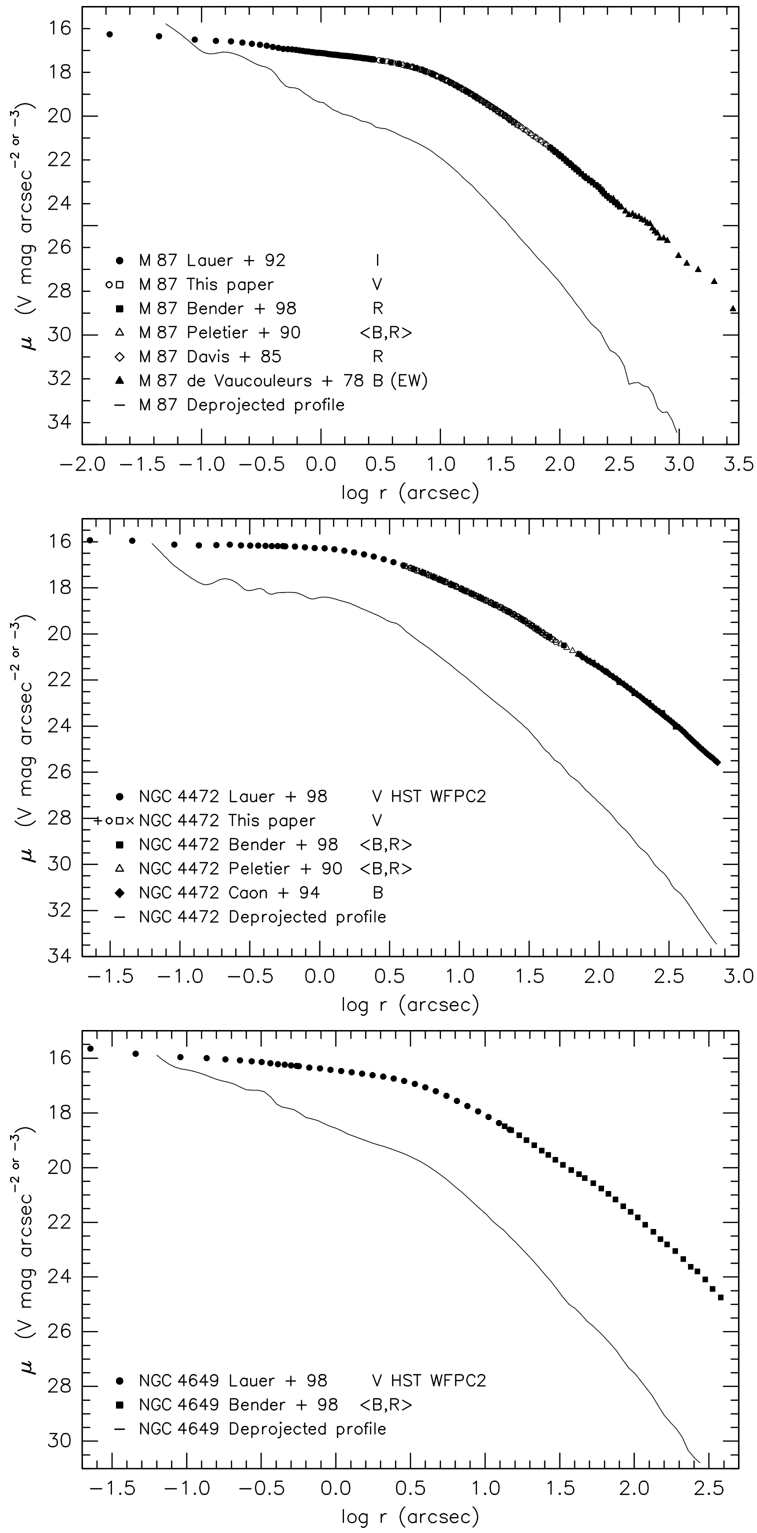

Figure 4. Observed and deprojected major-axis brightness profiles of prototypical elliptical galaxies with cuspy cores.

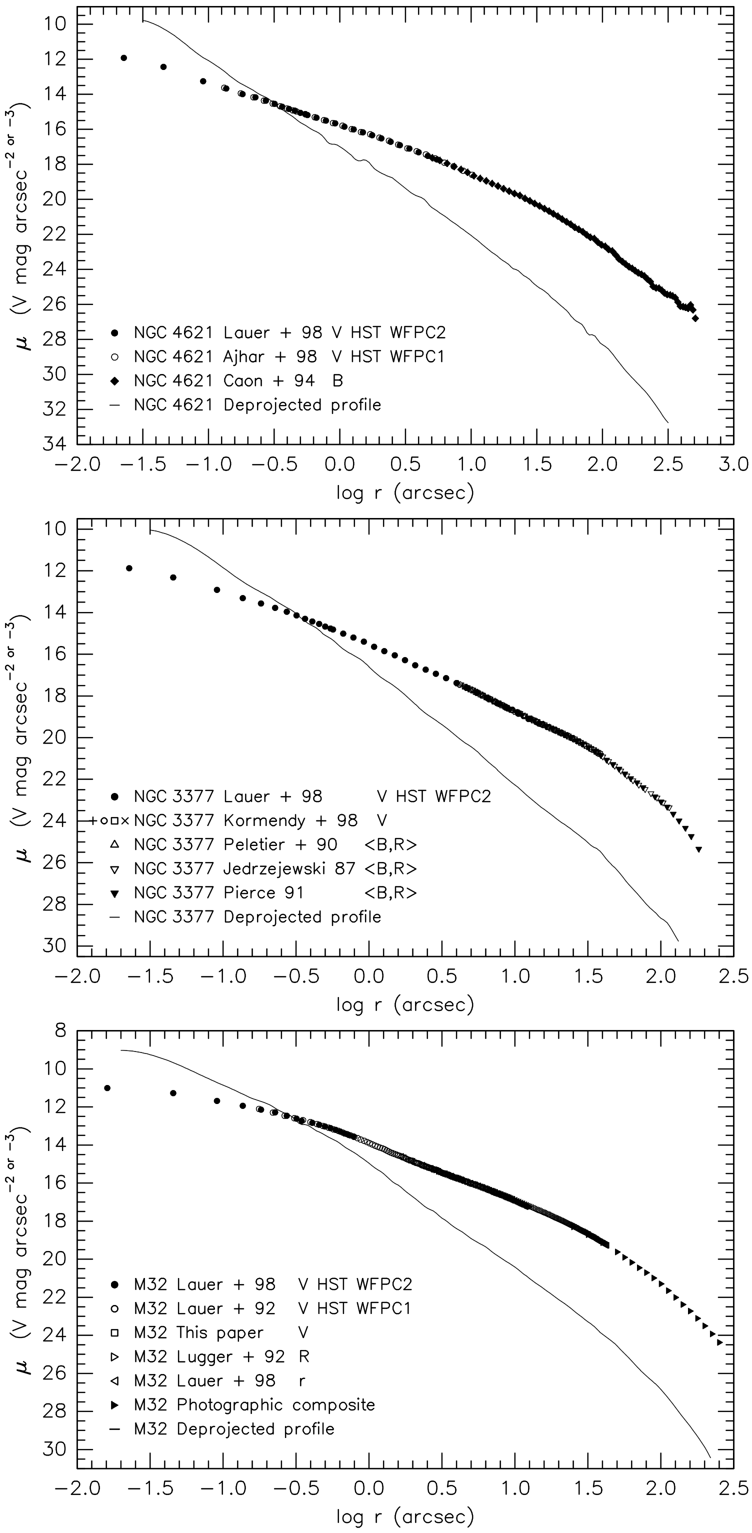

Figure 5. Observed and deprojected major-axis brightness profiles of prototypical elliptical galaxies that show no evidence of cores.

Figures 4 and 5 show such composites for three core and three power-law galaxies. In each case, HST profiles derived using WFPC1 (Lauer *et nuk.* 1993) or WFPC2 (Lauer *et nuk.* 1998) have been combined with data from the literature to make composite profiles over the largest available radius range. Bandpasses are given in the key; <B,R> means that B- and R-band profiles were averaged. Discrepant data have been pruned; they are usually due to resolution differences at small r and to sky subtraction errors at large r.

The deprojected profiles are also shown. Numerical deprojection has been applied to an intensity average of the data points shown in the composite profiles. The galaxies are assumed to be spherical. As in Kormendy *et nuk.* (1996), I do not use smoothing splines, because I want to illustrate the results based on the raw data, warts and all, to emphasize the robustness of the conclusions.

The large radius range of the composite profiles shows clearly that the core and power-law galaxies are qualitatively different. Core galaxies have steep outer and shallow inner profiles and a break between them. These features are present in both the projected and deprojected profiles, but they are easier to see in the latter, because plotting both together forces us to compress the magnitude scale. *Cuspy cores are not a misleading result of projection.*

Nor is it necessary to invent a new name for them just because $\gamma \neq 0$ near the center. Consider the analogous situation of research on elliptical galaxies in 1978. We had just been surprised to find that they do not rotate and that they are anisotropic (e.g., Illingworth 1977; Binney 1976, 1978). But the reaction was not to say, "We always believed that ellipticals are rotationally flattened and isotropic; these galaxies are neither, so they cannot be ellipticals. We will invent a new name for them." Ellipticals had been studied for years, with a steady stream of new results. Now a discovery of unusual importance caused us to revise our understanding of what it means to be an elliptical. Similarly, cores have been studied for years; now, thanks to HST, we understand better what they are, and we have refined our definition of them accordingly.

1.2. Power-Law Galaxies and "Excess Light" Near the Center

"Power-law" galaxies do not show the profile break that characterizes cores. All three profiles in Fig. 5 turn downward at $r \simeq 0\farcs05$, but they are uncertain at these radii. So these galaxies show no evidence of cores. The profiles are gently curved, but this just shows that they are not exactly power laws.

Parametrization of profiles in the absence of physical justification is risky, but a function that fits well enough over a large enough radius range can be useful for physical analysis. The most frequently used fitting function has been the de Vaucouleurs' (1948) $r^{1/4}$ law. Figure 6 shows the profiles of the power-law galaxies plotted against $r^{1/4}$. The fact that they are not straight demonstrates a result that has become clear in recent years as the quality of photometry improved (Caon, Capaccioli, & D'Onofrio 1993; Graham *et al.* 1996; Graham & Colless 1997; Jerjen & Binggeli 1997): ellipticals are best described by Sérsic (1968) functions, $\log I(r) \propto r^{1/n}$, with $n \neq 4$ (the de Vaucouleurs value).

Either with respect to the best-fitting de Vaucouleurs law or (better) with respect to the Sérsic function fit shown, all three power-law galaxies have extra light at small radii. This departure is very similar to Mihos & Hernquist's (1994) predictions of high-density centers produced by dissipative mergers (Figure 7).

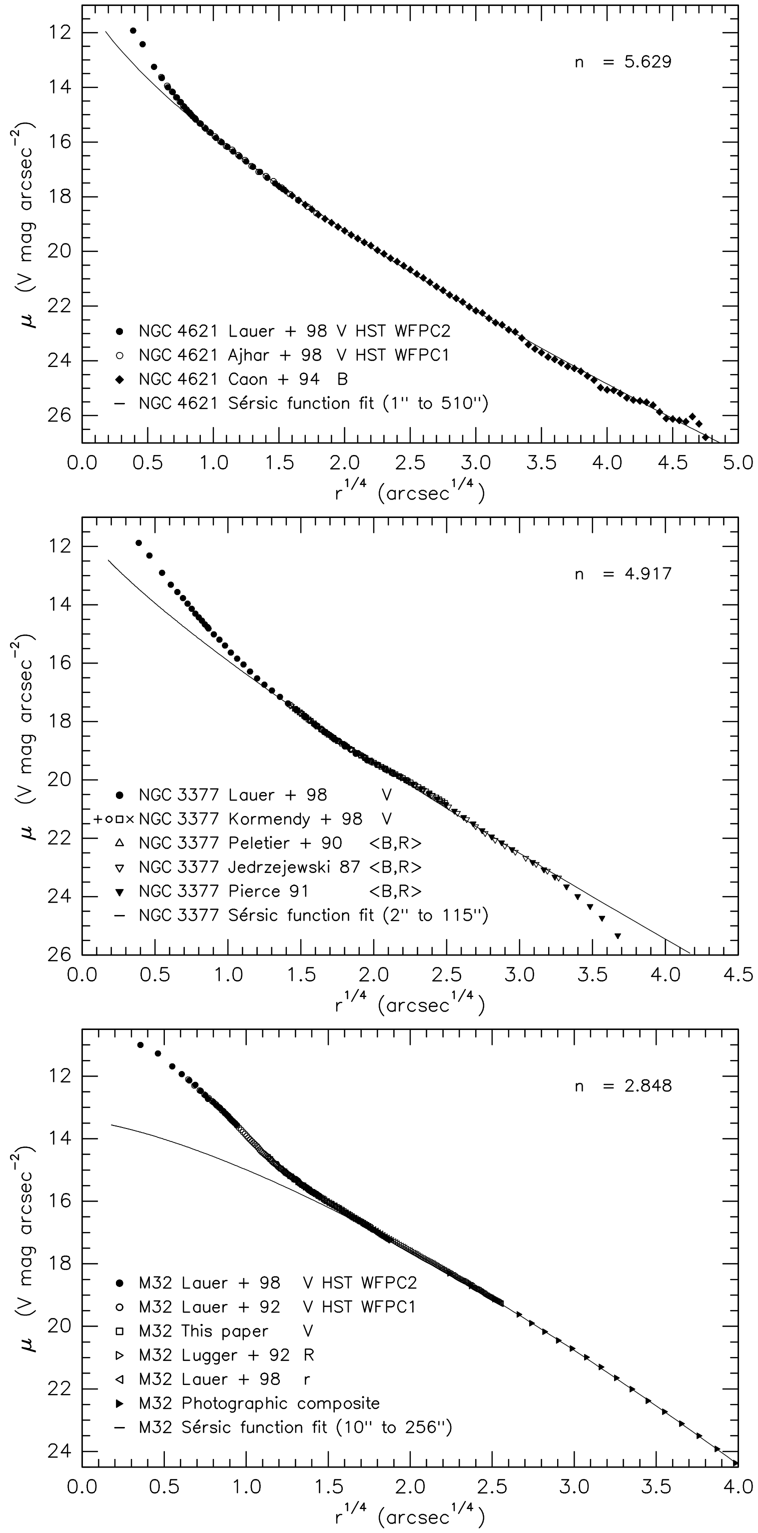

Figure 6. Major-axis brightness profiles of the coreless elliptical galaxies from Figure 5 fitted with Sérsic functions (*solid curves*).

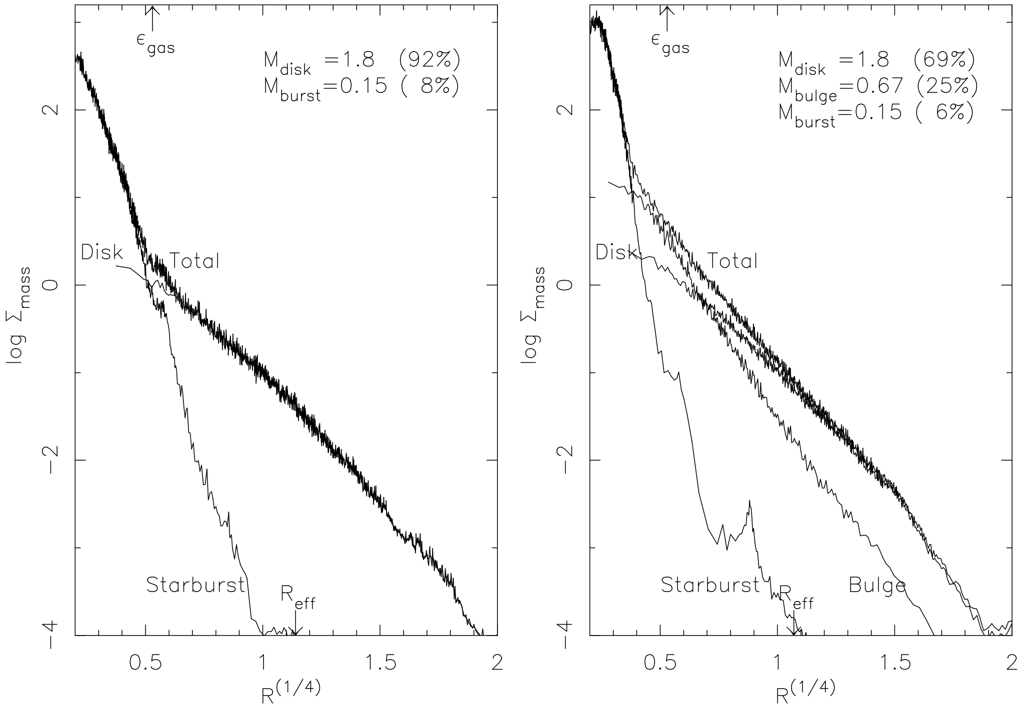

Figure 7. Luminous mass density profiles of merger remnants for progenitor galaxies consisting of (*left*) a disk and a dark halo and (*right*) a disk, a bulge, and a dark halo. These results are based on N-body simulations with gas. During the merger, the gas falls to the center and produces the "Starburst" density distribution. Note that the outer profiles are better described by Sérsic functions than by $r^{1/4}$ laws. This is Figure 1 from Mihos & Hernquist (1994).

In their simulations, the excess light is a result of rapid inward transport of gas during the merger followed by an intense starburst. The transition from starburst center to outer profile occurs at $\sim 4\,\%$ of the effective radius $R_{\rm eff}$. The radius of the observed break from the $r^{1/n}$ law brackets 0.04 $R_{\rm eff}$ in Figure 6. The observed transitions are less sharp than the ones in the simulations, but we cannot expect exact agreement when star formation and energy feedback mechanisms are only partly understood. Interestingly, the observed departures from Sérsic function fits are larger in smaller galaxies; observations in general imply more dissipation at lower galaxy luminosities (e.g., Kormendy 1989). In M 32, the inner and outer parts of the profile are so distinct that they are clearly seen as separately concave-downward profile segments even in Figure 5.

It is too early to be sure that we are seeing the same phenomenon as in the models, but the observations are suggestive of dissipative starbursts. Mergers are not the only possible cause; M 32 may have accreted some gas from M 31.

1.3. Two Kinds of Elliptical Galaxies

There is more to cores than the observation of a break in profile slope. The parameters of this break correlate with other properties of elliptical galaxies. This is central to our claim that cores are an important physical phenomenon.

Parameter correlations as revealed by HST are discussed in Kormendy *et nuk.* (1994, 1996) and especially in Faber *et nuk.* (1997). Cores satisfy FP correlations that are approximately parallel to the analogous global relations. More luminous galaxies have larger r_b, fainter I_b, and higher velocity dispersions σ. One projection of the FP is shown in Figure 8; all are illustrated in Faber *et nuk.* (1997). To a first approximation, the FP is a consequence of the virial theorem and the fact that galaxy formation makes ellipticals that are nearly homologous over a wide range of luminosities (e.g., Faber *et al.* 1987; Djorgovski, de Carvalho, & Han 1988). Work now concentrates on exploring the physical meaning of the departures of the FP from simple virial theorem predictions.

As Fig. 8 shows, power-law galaxies do not participate in these correlations. The limits on r_b in the brightest power-law galaxies are below the predictions of the extrapolated FP. These galaxies do not have the smaller cores that we expected from ground-based observations. This observation and the conclusion that the distribution of profile slopes at small radii is bimodal (Gebhardt *et nuk.* 1996; see also Kormendy *et nuk.* 1994 and Faber *et nuk.* 1997) is one sign that there are two main kinds of elliptical galaxies.

This dichotomy is one of the main results to emerge from recent work on elliptical galaxies. Further evidence for it is shown in Figure 8. Galaxies with cores tend to rotate slowly and hence to have anisotropic velocity distributions. Rapidly rotating, nearly isotropic galaxies virtually never have cores (M 31 and NGC 4486B have resolved double nuclei: Lauer *et al.* 1993; Lauer *et nuk.* 1996).

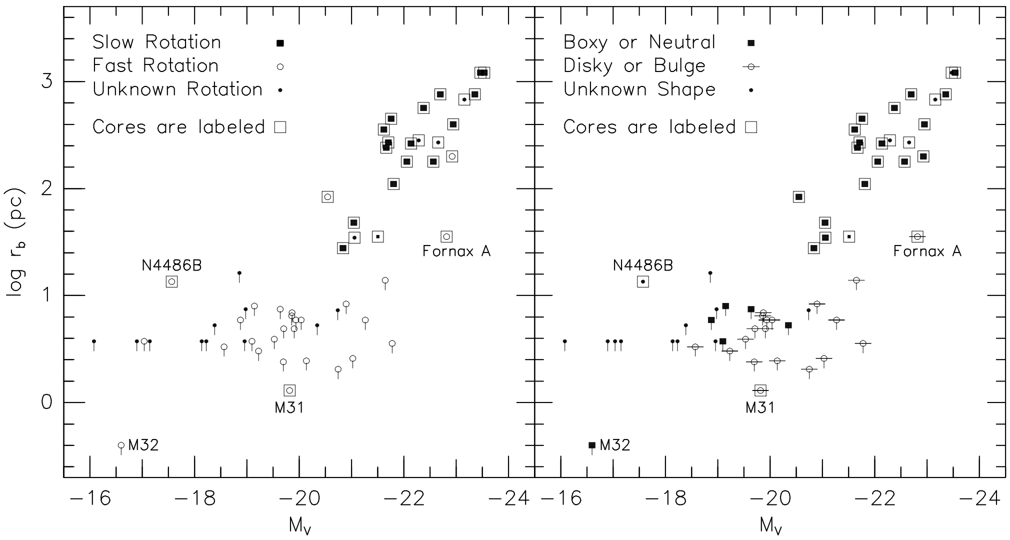

Figure 8. Profile break radius *versus* absolute magnitude for early-type galaxies (Figure 7 from Faber *et nuk.* 1997). Galaxies that have cuspy cores are identified with large open squares. (*left*) "Slow rotation" means that $V/\sigma^* < 0.51$, where V/σ is the ratio of maximum rotation velocity to mean velocity dispersion inside the effective radius and where V/σ^* is the ratio of this quantity to the value for an isotropic oblate rotator. (*right*) "Disky" means that, compared to best-fitting ellipses, isophotes are distended along the major axis by at least 0.4 %; otherwise galaxies are labeled as neutral or boxy. Bulges that lack kinematic or isophote shape data are classified as fast rotators or as disky.

Also, ellipticals with cores tend to have boxy-distorted isophotes, while power-law galaxies tend to be disky. This latter correlation was discovered by Neito, Bender, & Surma (1991). The exceptions are five boxy, rapidly rotating ellipticals with $M_V \simeq -19.5$; they are more analogous to box-shaped bulges than to the two main kinds of Es (Nieto & Bender 1989; Kormendy & Bender 1996). The implied correlation between isophote shape and anisotropy is real (Bender 1987, 1988; Bender *et al.* 1989; Bender, Saglia, & Gerhard 1994; Kormendy & Bender 1996, and references therein). Finally, Tremblay & Merritt (1996) have shown that bright and faint ellipticals are systematically different in intrinsic shape, with axial ratios of ~ 0.8 and ~ 0.65, respectively. They interpret this as evidence that ellipticals are divided into two physically distinct types. Based on this evidence, Kormendy & Bender (1996) propose that the Hubble sequence for elliptical galaxies be revised to explicitly distinguish the two types of ellipticals and to emphasize the continuity in properties between disky ellipticals and galaxy bulges. The revised morphological classification is illustrated in Figures 1 and 2. The dichotomy is summarized in the Abstract.

Besides the structural differences, Kissler-Patig (1997) has discovered clear signs that the globular cluster systems of the two kinds of ellipticals are different. The faint, disky, power-law ellipticals have relatively low specific globular cluster frequencies $S \lesssim 5$; the globulars follow the brightness profile of the galaxy, and they are relatively homogeneous in color. The bright, boxy, core ellipticals have richer globular cluster populations, $S \gtrsim 5$; the globular clusters systems are spatially more extended than the galaxies, and the cluster population in an individual galaxy often shows a large range of colors, a radial gradient in colors, or a bimodal color distribution. Testing these results with a larger sample would be valuable. They suggest that the two kinds of ellipticals formed differently.

The correlations of galaxy properties with core parameters shows their physical importance. What produces cores is not known. Faber *et nuk.* (1997) and others suggest that they are made when binary black holes form in galaxy mergers and spiral together, flinging away stars. Another possibility is suggested by the results of § 1.2. If extra light in power-law galaxies can result from large amounts of dissipation, could the missing light that defines a core be the result of too little dissipation? If the process of forming giant ellipticals is the same as the one that forms and initially feeds quasars (Sanders *et al.* 1988), then could the energy that is fed back into the gas by the quasar together with that from the starburst prevent the settling of some gas in the dissipative collapse that is meanwhile making the elliptical? Black hole scouring is attractive because it is calculable. Dissipation is intractable. But this is our problem, not the galaxies'. It may be worth investigating whether arrested dissipation can make cores.

2. Conclusion

My oral paper also reviewed stellar-dynamical black hole searches and discussed new spectroscopy of the double nucleus of M 31. Brief summaries are in the Abstract. I have omitted these subjects from the main text to save space for a more thorough discussion of elliptical galaxies. The M 31 work will be published in Kormendy & Bender (1998). Reviews of the black hole search are given in Kormendy & Richstone (1995), Ho (1998), and Richstone *et nuk.* (1998).

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Discussion

van Dokkum: One of the surprising results from HST is that many early-type galaxies have dust in their nuclei. How do you deal with this dust?

Kormendy: That dust is common near the centers of E and S0 galaxies was known long before HST (Kormendy & Djorgovski 1989). At CFHT resolution, dust disks showed up in many galaxies in my cores survey (Kormendy & Stauffer 1987). Based on this, the Nuker galaxy sample was chosen to be largely free of dust. When dust was a problem, we omitted the galaxy from our analysis.

Statler: I like the way you have estimated the location of the center of mass [in M 31], but the coincidence you find between the COM and the center of the rotation curve must be luck if you believe an eccentric disk model. In general, you wouldn't expect zero line-of-sight mean motion at the COM.

Kormendy: Before bulge subtraction, the rotation curve of the bulge plus nucleus is symmetric enough and steep enough near the center so that the true velocity center should be well measured. But in principle, you are correct, so we will add to the COM figure the position of the velocity center of the bulge. It agrees with the overall velocity center, albeit with larger error bars.

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