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Interpreting the Nuclear Cusp Slopes and Cores in Early-Type Galaxies

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Abstract

The relation between the central cusp slopes, core parameters, and black hole masses in early-type galaxies, is examined in light of two models that attempt to explain the formation of cores and density cusps via the dynamical influence of black holes. Contrary to the expectations from adiabatic-growth models, we find that the cusp slopes do not steepen with increasing black hole mass fraction. A comparison of kinematic black hole mass measurements with the masses predicted by the adiabatic models shows that they overpredict the masses by a factor of $\sim$3. Simulations involving binary black hole mergers predict that both the size of the core and the central mass deficit correlate with the final black hole mass; these relations are qualitatively supported by the data.

1.1 Introduction

The central surface brightness (SB) profiles in early-type galaxies can be parameterized by a single power law in galaxies where no core is resolved (power-law galaxies), while others require a double power law such that the slope within the resolved core is much shallower than the outer slope (core galaxies) (Kormendy 1985; Lauer 1985; Lauer et al. 1995). Core galaxies are luminous ($M_V \lesssim -21$ mag), have high velocity dispersions, boxy or elliptical isophotes, and show slow rotation. On the other hand power-law galaxies have lower luminosities and velocity dispersions, and are fast rotators with disky isophotes (Faber et al. 1997; Ravindranath et al. 2001; Rest et al. 2001). Thus, it appears that the origin of the inner cusps is closely linked to the formation and subsequent evolution of these galaxies. The steep density cusps seen in low-luminosity elliptical galaxies can result from dissipative, gas-rich mergers. However, an analogous scenario for the weak cusps seen in core galaxies, which involves dissipationless, gas-poor mergers conflicts with the empirical trend that giant ellipticals tend to have large-sized, diffuse cores (Faber et al. 1997).

Numerical simulations that include the dynamical effects of central black holes (BHs) have proved to be more promising in reproducing the low-density cores seen in luminous ellipticals (Ebisuzaki, Makino, & Okumura 1991; Nakano & Makino 1999; Milosavljević & Merritt 2001). In the merger models, the formation and subsequent orbital decay of a BH binary can destroy the existing steep cusps of the merging galaxies via the interaction of the binary with surrounding stars. These models predict that the scouring action by the BH binary would lead to the formation of a core whose properties are related to the final BH mass. An alternative model interprets the central cusps as the result of dynamical effects induced by the adiabatic growth of a central BH in an initially isothermal core (e.g., Young et al. 1978; van der Marel 1999). According to these models, the slope of the cusp is determined by the ratio of the BH mass to the mass of the initial core; a steeper cusp would result from a larger fractional BH mass. This is in contrast to the expectations of the merger models, where a more massive BH would cause the cusp to weaken.

In this presentation, we use a large database of observed central parameters of early-type galaxies to test the viability of the above models involving BHs. The sample used for the analysis is described in Ravindranath, Ho, & Filippenko 2002. Essentially, it comprises galaxies that have been observed using *HST* and for which the SB profiles (within a radius of $\sim 10''$) have been parameterized in the literature using the "Nuker" function (Lauer et al. 1995). This function has the form

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

where β is the asymptotic slope as $r \to \infty$, γ is the asymptotic slope as $r \to 0$, r_b is the break radius at which the change of slope occurs, I_b is the surface brightness at r_b, and α controls the sharpness of the transition between the inner and outer slope.

1.2 Comparison of Data with Model Predictions

Both the adiabatic-growth model and the binary BH model attempt to explain the formation of cores and weak cusps in elliptical galaxies based on the dynamical effects of BHs. We compare the relation between the observed quantities (core radius, inner-cusp slope, and BH mass) with the relations predicted from these models. The BH masses required for the analysis presented here are derived using the empirical correlation between BH mass and bulge stellar velocity dispersion (Gebhardt et al. 2000; Ferrarese & Merritt 2000).

1.2.1 Cusp Slopes and Black Hole Masses

The adiabatic-growth model predicts that more massive BHs produce steeper density cusps. Large values for the inner-cusp slope γ imply larger dimensionless BH mass $\mu \equiv M_{\rm BH}/M_{\rm core}$, where $M_{\rm core}$ is the mass of the initial isothermal core (Cipollina & Bertin 1994; van der Marel 1999). We do not have an independent estimate of $M_{\rm core}$, since the observed core properties, by assumption, have been altered by the BH. However, if we approximate the initial state of the galaxy by an isothermal sphere, the initial core radius would be a fixed fraction of the initial half-mass radius; $r_{\rm core} \approx 0.04\, r_e$, with a mean scatter of 0.23 dex about this relation (Ravindranath, Ho, & Filippenko 2002). Analogous to μ, we define the dimensionless mass $\mu' \equiv M_{\rm BH}/M_e$, where M_e is the mass within r_e calculated using $M_e = 3\sigma^2 r_e/G$.

A plot of the observed inner-cusp slope γ versus μ' (Fig. 1.1) appears to be inconsistent with the expected theoretical relation between γ and μ, given by Cipollina & Bertin (1994) for the adiabatic-growth model. The largest discrepancy lies with the power-law galaxies, because their steep cusps require them to have μ' up to 1–2 orders of magnitude larger than observed. Most power-law galaxies, in fact, are characterized by values of μ' within the fairly restricted range found in core galaxies ($\log \mu' \approx -2.9 \pm 0.5$). Since M_e and γ are vulnerable to distance effects, this test may be affected, at least in part, by uncertainties in the distances used. Following the arguments given in Ravindranath, Ho, & Filippenko

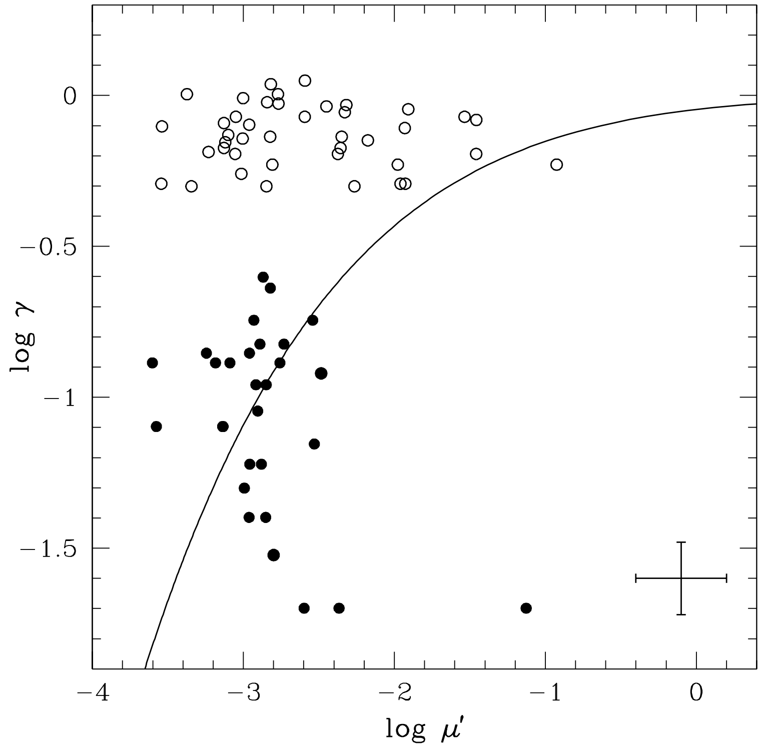

Fig. 1.1. The inner-cusp slope γ versus the dimensionless BH mass μ'. Core galaxies are shown as solid points and power-law galaxies as open circles. The solid line gives the theoretical prediction from Cipollina & Bertin (1994) for the relation between γ and μ, shifted arbitrarily along the horizontal axis to allow for a constant scaling between μ and μ'.

(2002) we do not believe that distance errors could have erased an intrinsic trend in Fig 1.1. The adiabatic models also tend to yield BH masses that are systematically larger, on average by ∼0.5 dex compared to measured BH masses; the offset is slightly larger for power-law galaxies than core galaxies (Fig 1.2).

1.2.2 Core Properties and Black Hole Binaries

Simulations of merging galaxies with central BHs produce merger remnants whose core properties correlate well with the final BH mass (Ebisuzaki et al. 1991; Nakano & Makino 1999; Milosavljević & Merritt 2001). Larger BHs tend to create larger and more massive cores (Nakano & Makino 1999). Figure 1.3*a* shows the relation between the observed core size represented by the break radius r_b, and the BH mass. Albeit with substantial scatter, the observed trend qualitatively agrees with the simulations in that more massive BHs produce larger cores. According to binary BH merger models, more luminous galaxies should have experienced a larger number of mergers than fainter galaxies, and hence their centers should have been "scoured" more thoroughly by the orbital decay of BH binaries. A key prediction from the simulations by Milosavljević & Merritt (2001) is that the mass ejected during each merger event by the

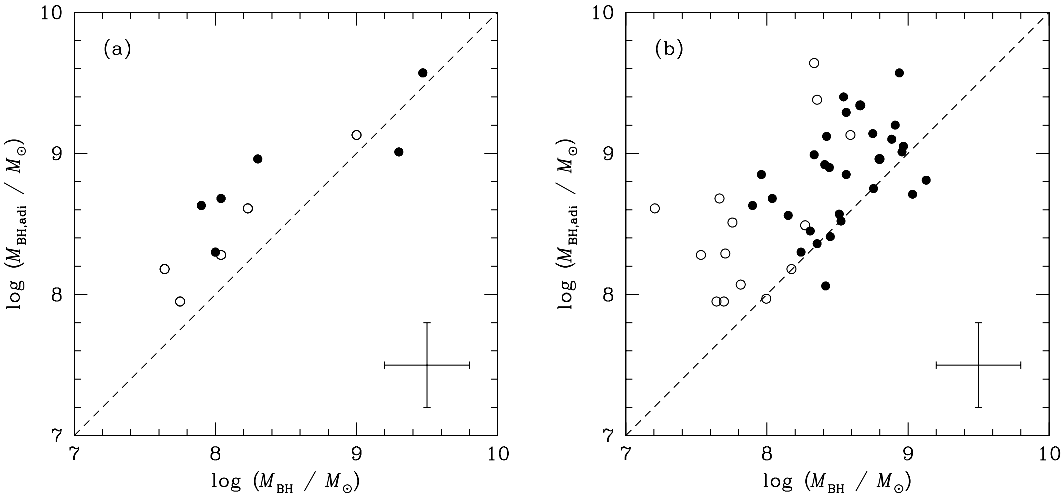

Fig. 1.2. Comparison of BH masses obtained from the adiabatic-growth models of van der Marel (1999) with (*a*) BH masses derived directly using stellar and gas kinematics (Kormendy & Gebhardt 2001) and (*b*) BH masses derived using the $M_{\rm BH}-\sigma$ relation from Gebhardt et al. (2000). The solid points correspond to core galaxies and open circles to power-law galaxies.

BH binary should be comparable to their combined mass. The ejected mass is given by the expression, $M_{\rm ej} \approx \frac{2(2-\gamma')}{3-\gamma'} \frac{\sigma^2 r_b}{G}$, where r_b is the core radius (equivalent to the break radius in the Nuker function) and γ' is the inner-cusp slope of the luminosity density profile. The total mass ejected depends on the final BH mass and the number of mergers, and hence a steeper-than-linear relation is expected between the mass deficit and BH mass. A plot of $M_{\rm ej}$ versus $M_{\rm BH}$ (Fig. 1.3*b*) shows that the two quantities are indeed well correlated.

1.3 Discussion

The existing data on the observed properties of the cores in luminous galaxies support the notion that they have been substantially molded by the dynamical influence of binary massive BHs during past merger events (Ravindranath, Ho & Filippenko 2002; Milosavljević et al. 2002). In simulations involving two low-mass galaxies, each containing a central BH and a steep nuclear cusp, the hardening of the BH binary leads to the formation of a remnant with a large, diffuse core (Milosavljević & Merritt 2001). The predicted steeper-than-linear relation between the $M_{\rm BH}$ and $M_{\rm ej}$, arising from the dependence of the total ejected stellar mass on the number
of merger events, is qualitatively confirmed by the data; we find that $M_{\rm ej} \propto M_{\rm BH}^{2.3}$ (Fig. 1.3*b*). The exact slope should depend on complications not treated in the models, such as heterogeneous mergers and gas accretion. If cores form as an aftermath of galaxy mergers containing BHs, the sizes of the cores should scale with the final BH mass (Nakano & Makino 1999). We find that this is consistent with the data: core size increases roughly as $r_b \propto M_{\rm BH}^{2.8}$ (Fig. 1.3*a*). We note that unlike the case of the relation between r_b and $M_{\rm BH}$, the slope of

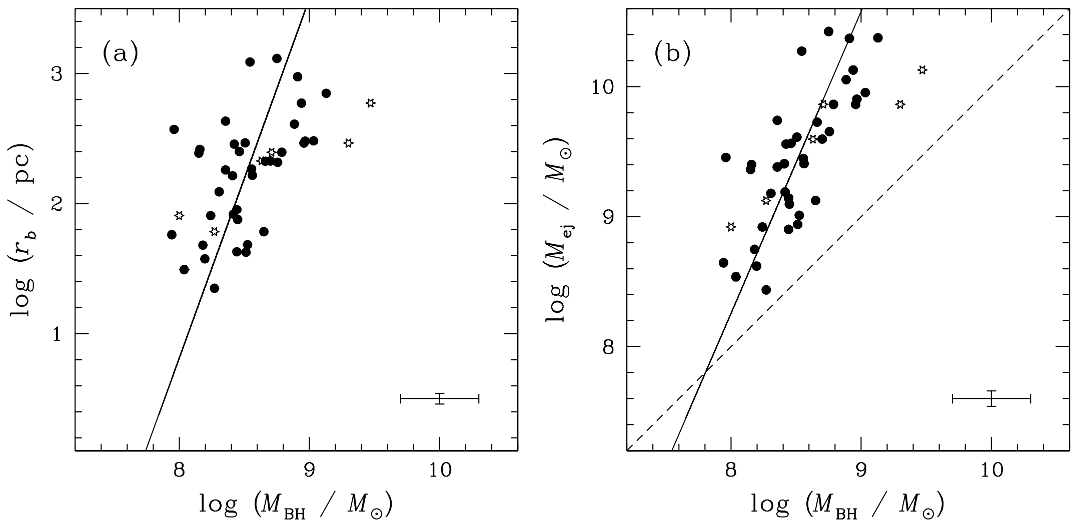

Fig. 1.3. The relation among core galaxies between BH mass $M_{\rm BH}$ and (*a*) the break radius r_b and (*b*) the ejected mass $M_{\rm ej}$. The solid line in each panel gives the best-fitting linear regression. The dashed line in panel (*b*) denotes $M_{\rm ej} = M_{\rm BH}$. The open star symbols replot the six galaxies whose BH masses have been measured directly by kinematics. They do not show any obvious systematic deviations compared to the solid points.

the correlation between $M_{\rm ej}$ and $M_{\rm BH}$ cannot be easily traced to known central-parameter scaling relations (Ravindranath, Ho & Filippenko 2002).

According to the adiabatic BH growth picture, for a galaxy core of a given mass, a more massive BH induces a steeper cusp. The observed cusp slopes do not appear to comply with the expectations of this model. The strongest disagreement comes from the power-law galaxies, whose steep cusps would suggest that these objects have exceptionally large BH mass fractions, contrary to what is actually observed (Fig. 1.1). Therefore, it is surprising that the $M_{\rm BH}$ derived from the adiabatic models (van der Marel 1999) differs from the actual masses by just $\sim$0.5 dex (Fig. 1.2). However, given that the models were fitted to the core regions whose size, r_b is typically only a factor of a few larger than the "sphere of influence" of the BH, the mass scale of the initial core (set by the core size), should be comparable to the BH mass. The larger offset between the model-inferred BH masses and the actual BH masses for power-law galaxies compared to core galaxies (Fig. 1.2) is a simple consequence of the fact that the adiabatic models need to invoke larger BH mass fractions (μ) to fit power-law galaxies than in core galaxies, whereas empirically both types of galaxies share rather similar BH mass fractions.

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