Galaxy Cores as Relics of Black Hole Mergers

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1 INTRODUCTION

Ferrarese et al. (1994) and Lauer et al. (1995) divide elliptical galaxies into two classes based on their nuclear properties, which Lauer et al. call “core” and “power-law” galaxies. Core galaxies exhibit a definite break in the surface brightness profile at some radius $R_b$; inward of this break, the logarithmic slope gently decreases in a manner that mimics a constant-density core. Power-law galaxies show essentially a single power-law profile throughout their inner regions, $\Sigma(R) \sim R^{-\Gamma}$, $\Gamma \approx -0.8 \pm 0.2$. The brightest galaxies, $M_V \lesssim -21$, are exclusively core galaxies while fainter galaxies, $M_V \gtrsim -16$ always exhibit power laws; galaxies of intermediate luminosity can exhibit either type of profile (Gebhardt et al. 1996). While the two categories were initially seen as distinct, nonparametric deprojection revealed that even the “core” galaxies exhibit power laws in their central space densities, $\rho \sim r^{-\gamma}$, with $\gamma \lesssim 1$ (Merritt & Fridman 1995). Power-law galaxies have $1 \lesssim \gamma \lesssim 2.5$ (Gebhardt et al. 1996). Furthermore the distribution of de-projected slopes is essentially continuous as a function of galaxy luminosity in the large samples now available (Ravindranath et al. 2001; Rest et al. 2001).

Here we assume that the steep central density cusps of faint ellipticals and bulges, $\rho \sim r^{-2}$, are characteristic of the earliest generation of galaxies, and ask: How do the low-density cores associated with bright galaxies form? An appealing hypothesis links cores to nuclear black holes (BHs): in a galactic merger, the BHs will fall to the center of the merger remnant and form a bound pair, releasing their binding energy to the surrounding stars (Begelman, Blandford & Rees 1980; Ebisuzaki, Makino & Okumura 1991). High-resolution $N$-body simulations verify that this process can convert a steep power-law cusp, $\rho \sim r^{-2}$, into a shallow power-law cusp, $\rho \sim r^{-1}$, within the radius of gravitational influence of the BHs (Milosavljević & Merritt 2001). Successive mergers would presumably lower the density of the core still more. In this model, power-law galaxies are those which have not experienced a major merger since the era of peak BH growth, or which have re-generated their cusps via star formation (Milosavljević & Merritt 2001).

Preliminary tests of the cusp-disruption model were presented by Faber et al. (1997) and Milosavljević & Merritt (2001). The former authors plotted core properties (break radius, core luminosity) versus global properties in a sample of 19 early-type galaxies and noted a rough proportionality. In the paradigm investigated here, core properties should correlate more fundamentally with BH mass, since the mass of stars ejected by a decaying binary BH is expected to be of order the BHs’ mass. Milosavljević & Merritt (2001) used the new empirical relation between galaxy velocity dispersion and BH mass, the $M_{\bullet} - \sigma$ relation (Ferrarese & Merritt 2000; Gebhardt et al. 2000), to estimate BH masses in the Faber et al. sample. They found that a rough dynamical estimate of the “mass deficit” – the mass that would need to be removed from an initially $r^{-2}$ density cusp in order to produce the observed profile – correlated well with $M_{\bullet}$.

In this paper we present the most careful test to date of the BH merger hypothesis for the formation of galaxy cores. We use nonparametric deprojection to compute the mass...
deficit in a sample of galaxies with high-resolution imaging data from HST (§2). We find a strong correlation between this mass and the mass of the nuclear BH; typical ejected masses are ~ several $M_\star$ (§3). We argue (§4) that this result is consistent with the formation of cores via hierarchical mergers of galaxies containing pre-existing BHs. Cusps of non-interacting dark matter particles should behave in the same way as cusps of stars in response to heating by binary BHs, and we argue that the damage done to stellar cusps by this mechanism is a reasonable guide to the damage that would be done to dark matter cusps.

2 DATA AND METHOD

Our data set is drawn from a sample of 67 surface brightness profiles of early-type galaxies observed with HST/WFPC2 by Rest et al. (2003), and three additional galaxies: NGC 4472 and 4473, observed with WFC1 by Ferrarese et al. (1995), and a WFPC2 F547M image of M87 (Jordan et al. 2002). The Rest et al. sample was selected from a set of all early-type galaxies with radial velocities less than 3400 km s\(^{-1}\), absolute V-band magnitudes less than ~18.5, and absolute galactic latitude exceeding 20 degrees. From this sample we excluded 13 galaxies for which central velocity dispersions were not available in literature; as discussed below, velocity dispersions were needed to compute BH masses in most of the galaxies. For specifics of the image-data reduction we refer the reader to the sources cited above. Surface brightness profiles used in this study were major-axis profiles. We applied a crude correction for the apparent ellipticity of the galaxies by multiplying the volume-integrated quantities, defined below, by (1 - $\epsilon_0$), where $\epsilon_0$ is the ellipticity of the isophote at the break radius.

The intrinsic luminosity profiles $\nu(r)$ were obtained by deprojecting the PSF-deconvolved surface brightness profiles $\Sigma(r)$ using the non-parametric MPL technique (Merlotti & Tremonti 1999). We opted for one-step deprojection via maximization of the penalized likelihood functional

$$L_\lambda[\nu] = \sum_i \frac{(\Sigma_i - P_i[\nu])^2}{(\Sigma_i^{\text{proj}})^2} - \lambda \int_0^\infty \left[ \frac{d^2 \log \nu}{(d \log r)^2} \right]^2 d \log r. \quad (1)$$

The first term compares the observed surface brightness data $\Sigma_i \equiv \Sigma(R_i)$ to the projections $P_i[\nu]$ of the intrinsic luminosity estimate $\nu$ given by the operator

$$P_i[\nu] = 2 \int_{r_i}^{\infty} \frac{\nu(r)rdr}{\sqrt{r^2 - r_i^2}}. \quad (2)$$

The second term in equation (1) is the penalty function which assigns zero penalty to any power-law $\nu(r)$; hence our estimate of $\nu$ is unbiased if $\nu$ is an unbroken power law and should be minimally biased if $\nu$ is approximately a power law. The relative strength of the penalty term is regulated through the parameter $\lambda$ which was chosen by eye and equal to 0.01 for all galaxies; integrated quantities like the mass deficit defined below are only weakly dependent on $\lambda$.

Distances for 26 of the galaxies were drawn from the SBF survey (Faber et al. 2001). For the remaining 34 galaxies we adopted distances computed assuming a pure Hubble expansion with $H_0 = 80$ km s\(^{-1}\) Mpc\(^{-1}\) corrected for Virgo-centric infall (Rest et al. 2001). Luminosity densities were converted to mass densities $\rho(r) = \Upsilon \nu(r)$ using the individual mass-to-light ratios $\Upsilon$ quoted in Magorrian et al. (1998) or their best-fit relation $log(\Upsilon/V)$ or galaxies not included in that study.

We define $\gamma \equiv -d\log \rho(r)/d\log r$ as the local, negative logarithmic slope of the deprojected density profile. Power-law galaxies are defined as those in which $\gamma \geq 2$ at all radii; typically the profiles of such galaxies show no clear feature that can be identified as a “break radius” and are unlikely candidates for cusp destruction by binary BHs. In the remaining 35, “core” galaxies, the slope varies from $\gamma > 2$ at large radii to $\gamma < 2$ at small radii; the radius at which the slope crosses $\gamma = 2$ in the positive sense ($d\gamma/dr > 0$) is called here the “break radius” $r_b$ (Figure 1). This definition has little in common with the more standard definition based on fitting of the surface brightness profile to an ad hoc parametric function. In four galaxies the slope crosses $\gamma = 2$ in the positive sense at more than one radius and thus the definition of $r_b$ is ambiguous. In such cases, we select the crossing toward larger radius from the largest dip of the slope below $\gamma = 2$.

We define the mass deficit as the difference in integrated mass between the deprojected density profile $\rho(r)$ and a $\gamma = \gamma_0 = 2$ profile extrapolated inward from the break radius:

$$M_{\text{def}} \equiv 4\pi(1 - \epsilon_0) \int_0^{r_b} \rho_r \left( \frac{r}{r_b} \right)^{-\gamma_0} - \rho(r) \right) r^2 dr. \quad (3)$$

Our choice of an $r^{-2}$ density profile to characterize the “undisrupted” core is to a certain extent arbitrary; adiabatic growth of BHs can produce cusps with $1.5 \lesssim \gamma \lesssim 2.5$ depending on initial conditions, and the faintest ellipticals with measured cusp slopes exhibit a similar range of $\gamma$'s (e.g., Gebhardt et al. 1996). To test the sensitivity of our results to the assumed initial profile, we repeated the analysis using fiducial slopes of $\gamma_0 = 1.75$ and 1.5. Values of $\gamma_0 > 2$ were found to exclude all but a few galaxies.

BH masses for a few of the galaxies in our sample are available from spatially-resolved kinematical studies (Merlotti & Ferrarese 2001). For all other galaxies we estimated $M_\star$ via the $M_\star - \sigma$ relation,

$$M_\star \approx 1.4 \times 10^8 M_\odot \left( \frac{\sigma_e}{200 \text{ km s}^{-1}} \right)^{4.8 \pm 0.5}. \quad (4)$$
where \( \sigma_c \) is the central velocity dispersion corrected to an aperture of \( r_e / 8 \) with \( r_e \) the effective radius. We used the aperture corrections of Jørgensen et al. (1993) to compute \( \sigma_c \) from published values of \( \sigma \) in Davies et al. (1987), Tonry & Davis (1984), and Di Nella et al. (1998).

3 RESULTS

Results are given in Tables 1 and 2 and Figure 2. Table 1 gives mass deficits only for \( \gamma_0 = 2 \) while Figure 2 shows \( M_{\text{def}} \) computed using all three values of the fiducial slope, \( \gamma_0 = (2, 1.75, 1.5) \). In the first panel of Figure 2 we have also plotted “dynamical” estimates of \( M_{\text{def}} \) for a sample of galaxies from Gebhardt et al. (1996), using equation (41) from Milosavljević & Merritt (2001). \( M_{\text{dyn}} \equiv 2(2 - \gamma)/(3 - \gamma)\sigma^2 R_b / G; M_{\text{dyn}} \) depends on the density profile only through \( R_b \), the break radius of the surface brightness profile, and \( \gamma \). When calculated for the deprojected galaxies in our sample, \( M_{\text{dyn}} \) was consistent within the scatter with \( M_{\text{def}} \).

For \( \gamma_0 = 2 \), the mass deficits are clustered about a linear relation defined by \( \langle \log (M_{\text{def}}/M_*) \rangle = 0.92, 1.0, \) and 0.65, respectively, for Es and S0s; Es only; and S0s only, corresponding to \( M_{\text{def}} \sim (8.4, 10, 4.5)M_* \). Decreasing \( \gamma_0 \) decreases \( M_{\text{def}} \) (cf. Fig. 1b) and \( M_{\text{def}} \) becomes negative/undefined in galaxies when the minimum pointwise slope \( \gamma_{\text{min}} \) approaches \( \gamma_0 \). We do not cite values of \( \langle \log (M_{\text{def}}/M_*) \rangle \) for these low values of \( \gamma_0 \) since the mean depends strongly on which galaxies are defined as having “cores.” However Figures 2b, c shows that \( M_{\text{def}} \) remains in order \( M_* \) or greater for many of the galaxies even when \( \gamma_0 < 2 \). We speculate that the lower mean value of \( M_{\text{def}} \) for the S0s may indicate a role for gaseous dissipation in the re-formation of cusps following mergers.

We emphasize, however, that the mass deficit of lenticulars alone appears to be completely uncorrelated with the BH mass.

Table 2 lists linear regression fits to the data that were carried out using the routine of Akritas & Bershady (1996). For the ellipticals (Rest et al. 2001) the fitted power-law indices of the \( M_{\text{def}} - M_* \) relation calculated with \( \gamma_0 = 2.0 \) and 1.75 are statistically consistent with unity. To test the sensitivity of the fitting parameters to the assumed power-law index \( \alpha \) of the \( M_* - \sigma \) relation (equation 2), we recomputed the fits with the Gebhardt et al. (2000) value \( \alpha = 3.75 \pm 0.3 \) in addition to the Ferrarese & Merritt (2000) value \( \alpha = 4.85 \pm 0.5 \) that is standard throughout the current paper. The effect of changing to a shallower version of the \( M_* - \sigma \) relation is a steepening of the \( M_{\text{def}} - M_* \) relation, from \( d \log M_{\text{def}} / d \log M_* \approx 0.91 \) to \( d \log M_{\text{def}} / d \log M_* \approx 1.16 \).

We note that in most galaxies the break radius defined via \( \gamma(r_b) = \gamma_0 = 2 \) is close to the radius at which the density profile exhibits a visual break, i.e., where the curvature is greatest. The break radius, however, is not a good predictor of the mass deficit; in particular, some galaxies with large break radii, \( r_b \gg r_e \), with \( r_e = GM_*/\sigma^2 \) the dynamical radius of the BH, have mass deficits below the mean. We speculate below that these large break radii may be produced by mechanisms other than BH mergers.

Although estimation of errors in Figure 2 is difficult, we believe that the scatter is at least partly intrinsic. Un-
uncertainties in log $M_{\bullet}$ are due primarily to uncertainties in $\sigma$ and are of order log 2. Uncertainties in log $M_{\text{def}}$ are also roughly log 2 based on variances between the redshift-based and SBF distances. A scatter greater than that due to measurement uncertainties would be reasonable given the different merger histories of galaxies with given $M_{\bullet}$. Similarly, if the progenitors of the galaxies exhibited a range of different $\gamma_0$, this could in itself explain the observed scatter in Figure 4.

4 DISCUSSION

The mass ejected by a decaying BH binary is

$$M_{ej} \approx J M_{1+2} \ln \left( \frac{a_h}{a_{gr}} \right)$$

(5)

where $M_{1+2} = M_1 + M_2$ is the binary mass, $a_h$ is the semi-major axis when the binary first becomes hard, and $a_{gr}$ is the separation at which the rate of energy loss to gravitational radiation equals the rate of energy loss to the stars. Quinlan (1996) claims that $J$ is a dimensionless mass-ejection rate; for equal-mass binaries, $J \approx 0.5$ (Milosavljević & Merritt 2001). Quinlan (1996) further shows that $J$ is nearly independent of $M_2/M_1$ even for extreme mass ratios, implying that a mass in stars of order $M_1 + M_2$ is ejected during every accretion event, even when $M_2$ is tiny compared with $M_1$. This non-intuitive result is due to Quinlan’s ejection criterion, which for $M_2 \ll M_1$ includes stars that would not have gained sufficient energy to escape from the binary. If instead we equate the change in energy of the binary with the energy carried away by stars that are ejected with $v \gtrsim V_{\text{bin}}$, we find $M_{ej} \approx M_2$. This argument suggests a relation

$$M_{ej} \approx M_2 \ln \left( \frac{a_h}{a_{gr}} \right)$$

(6)

which is consistent with equation (5) when $M_1 \approx M_2$.

Using equation (6), and adopting Merritt’s (2000) semi-analytic model for decay of a binary in a power-law cusp, we find

$$\frac{a_{gr}}{a_h} \approx A \ln A^{0.4}, \quad A \approx 7.5 \left( \frac{M_1}{M_2} \right)^{0.2} \frac{\sigma}{c}$$

(7)

and

$$M_{ej} \approx 4.6 M_2 \left[ 1 + 0.043 \ln \left( \frac{M_2}{M_1} \right) \right], \quad M_1 \leq M_2.$$ (8)

Thus $M_{ej}/M_2$ varies only negligibly with $M_1/M_2$. Henceforth we adopt $M_{ej} \approx 5M_2$.

If a BH grows by sequential accretion of smaller BHs, this result implies a mass deficit of order five times the final BH mass. However if the BH grows via a merger hierarchy of comparably-massive BHs, we expect $M_{\text{def}}$ to be larger. The idea here is that the damage done to cusps is cumulative: a merger of two galaxies whose cusps had previously been destroyed by binary BHs, will produce a shallower profile than a merger between two galaxies with initially steep cusps, even if the final BH mass is the same. Galaxies with masses $M \gtrsim 10^{11} M_\odot$, including most of the galaxies plotted on Figure 2, are believed to have undergone at least one major merger since a redshift of 1 (e.g. Kauffmann, Charlot & Balogh 2001). Thus we predict $M_{\text{def}} \gtrsim 5M_{\bullet}$, consistent with Figure 2 if $\gamma_0 \gtrsim 1.5$.

Our interpretation of the mass deficit depends critically on the assumption that all of the change in $\gamma$ during a merger can be attributed to the BHs, i.e., that cusp slopes remain unchanged the absence of BHs. This is known to be the case in equal-mass mergers between galaxies with power-law cusps (Barnes 1999, Milosavljević & Merritt 2001), though in mergers with extreme mass ratios, features can appear in the density profile that are not due to BHs (Merritt & Cruz 2001). We speculate that the break radii in some of the galaxies in our sample may be due to this process, particularly those galaxies (e.g., NGC 3640, 4168) where $r_h$ greatly exceeds the radius of gravitational influence of the BH. N-body simulations of cumulative mergers with unequal BH masses will be needed to assess this hypothesis.

Our model presents an interesting contrast to that of van der Marel (1999), who proposed that cores (in the sense of constant-density regions) were present in all galaxies ab initio, and that power-law cusps were generated by the growth of the BHs – roughly the opposite of our model in which BHs destroy pre-existing cusps. Van der Marel assumed that core mass correlated initially with bulge luminosity as $M_{\text{core}} \sim L^{1.5}$ and that $M_{\bullet} \propto L$; hence $M_{\text{core}} \propto M_{\bullet}^{1.5}$, consistent with the correlation in Figure 2 if we identify $M_{\text{core}}$ with $M_{\text{def}}$. We believe that this agreement is coincidental. Van der Marel’s model relates core mass to BH mass via an ad hoc postulate, while the model discussed here contains a mechanism for core formation. Van der Marel also ignored the effects of mergers. Nevertheless, van der Marel’s model shows that our interpretation is not unique.

If stellar cusps are destroyed by binary BHs, the same should be true of dark-matter cusps, like those predicted in CDM theories of structure formation (e.g., Navarro, Frenk & White 1996; Moore et al. 1999; Bullock et al. 2001). Destruction of dark matter cusps could be very efficient if supermassive BHs were present in dark matter halos at large redshifts (e.g., Fan et al. 2001; Haiman & Loeb 2001; Menou, Haiman & Narayan 2001) due to the cumulative effect mentioned above; furthermore, dark matter cusps would not be regenerated the way that stellar cusps might be via star formation. If our model for the formation of stellar cores is correct, we would predict that the cores of non-interacting CDM should be about as large as those observed in the stars, and perhaps larger.

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Table 1. Galaxies with $\gamma_{\text{min}} \leq 2$; $D$ is distance in Mpc; $r_b$ is break radius in kpc; $\gamma_{\text{min}}$ is the minimum logarithmic slope; $M_*$ and $M_{\text{def}}$ are in solar masses.

| Galaxy        | $D$ | $M_B$ | $r_b$ | $\gamma_{\text{min}}$ | $\log M_*$ | $\log M_{\text{def}}$ |
|---------------|-----|-------|-------|------------------------|------------|-----------------------|
| NGC 2549      | 12.6| -18.5 | 0.22  | 1.59                   | 7.91       | 8.46                  |
| NGC 2634      | 33.4| -19.9 | 0.27  | 1.73                   | 7.90       | 8.62                  |
| NGC 2986      | 26.8| -20.5 | 0.41  | 0.99                   | 8.79       | 9.51                  |
| NGC 3193      | 34.0| -20.9 | 0.23  | 0.84                   | 8.15       | 9.23                  |
| NGC 3348      | 38.5| -21.1 | 0.49  | 0.75                   | 8.47       | 9.79                  |
| NGC 3414      | 25.2| -20.1 | 0.14  | 1.61                   | 8.71       | 8.66                  |
| NGC 3613      | 29.1| -20.7 | 0.52  | 0.80                   | 8.20       | 9.39                  |
| NGC 3640      | 27.0| -21.0 | 0.68  | 0.94                   | 7.82       | 9.51                  |
| NGC 4121      | 28.3| -17.9 | 0.12  | 1.76                   | 7.06       | 7.94                  |
| NGC 4128      | 32.4| -19.8 | 0.18  | 1.64                   | 8.32       | 8.83                  |
| NGC 4168      | 30.9| -20.4 | 1.25  | 1.01                   | 7.90       | 9.58                  |
| NGC 4291      | 26.2| -19.8 | 0.17  | 0.49                   | 8.28       | 9.22                  |
| NGC 4365      | 20.4| -21.1 | 0.57  | 0.71                   | 8.50       | 9.79                  |
| NGC 4472      | 16.3| -21.7 | 0.63  | 0.90                   | 8.74       | 10.03                 |
| NGC 4473      | 15.7| -19.9 | 0.24  | 1.22                   | 7.90       | 9.25                  |
| NGC 4478      | 18.1| -19.1 | 0.30  | 1.42                   | 7.55       | 8.75                  |
| NGC 4486      | 16.1| -21.5 | 1.12  | 0.74                   | 9.55       | 10.49                 |
| NGC 4503      | 17.6| -19.2 | 0.25  | 1.56                   | 7.11       | 8.70                  |
| NGC 4564      | 15.0| -18.9 | 0.11  | 1.69                   | 7.76       | 8.22                  |
| NGC 4589      | 22.0| -20.0 | 0.18  | 1.05                   | 8.22       | 8.78                  |
| NGC 5077      | 34.0| -20.4 | 0.54  | 1.15                   | 8.78       | 9.51                  |
| NGC 5198      | 34.1| -20.0 | 0.11  | 0.92                   | 8.09       | 8.63                  |
| NGC 5308      | 26.6| -19.7 | 0.10  | 1.84                   | 8.37       | 8.01                  |
| NGC 5370      | 41.3| -19.0 | 0.32  | 1.56                   | 7.49       | 8.63                  |
| NGC 5557      | 42.5| -21.2 | 0.44  | 0.87                   | 8.64       | 9.62                  |
| NGC 5576      | 25.5| -20.3 | 0.24  | 1.37                   | 8.00       | 9.19                  |
| NGC 5796      | 36.5| -20.7 | 0.18  | 1.18                   | 8.60       | 9.15                  |
| NGC 5812      | 26.9| -20.3 | 0.25  | 1.71                   | 8.15       | 8.83                  |
| NGC 5813      | 32.2| -21.1 | 0.43  | 0.31                   | 8.40       | 9.66                  |
| NGC 5831      | 27.2| -19.9 | 0.22  | 1.42                   | 7.72       | 8.67                  |
| NGC 5898      | 29.1| -20.4 | 0.33  | 1.34                   | 8.30       | 9.20                  |
| NGC 5903      | 33.9| -20.9 | 0.78  | 0.87                   | 8.41       | 9.57                  |
| NGC 5982      | 39.3| -20.9 | 0.45  | 0.49                   | 8.71       | 9.58                  |
| NGC 6278      | 37.1| -19.7 | 0.10  | 1.53                   | 7.64       | 8.59                  |
| UGC 4551      | 23.6| -18.7 | 0.24  | 1.36                   | 8.02       | 8.87                  |

Table 2. Linear regression fits to the $(\log M_*, \log M_{\text{def}})$ data for three values of the fiducial logarithmic slope $\gamma_0$. Values in parentheses are $M_{\text{def}}/M_*$ interpolated from the fit at $M_* = 10^8 M_\odot$. Fourth and fifth columns are, respectively, fits of the entire data set (including the galaxies with dynamical estimates of $M_{\text{def}}$) using the Ferrarese & Merritt (2000) and the Gebhardt et al. (2000) values of the $M_* - \sigma$ relation exponent $\alpha$.

| $\gamma_0$ | E | S0 | $\alpha = 4.8$ | $\alpha = 3.75$ |
|------------|---|----|----------------|------------------|
| 2.00       | 0.93±0.10 | -0.10±0.14 | 0.91±0.09 | 1.16±0.12 |
| (10.5±1.8) | (3.8±0.86) | (9.75±1.78) | (10.7±1.7) |
| 1.75       | 1.07±0.15 | -0.78±0.46 | 0.86±0.24 | 1.10±0.30 |
| (2.75±0.78) | (0.35±0.19) | (2.17±0.50) | (2.36±0.56) |
| 1.50       | 1.56±0.37 | 1.58±0.35 | 2.02±0.45 | (0.49±0.26) |
| (0.46±0.23) | (0.55±0.25) | (0.55±0.25) | (0.55±0.25) |