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CORE DEPLETION FROM COALESCING SUPERMASSIVE BLACK HOLES

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ABSTRACT

New measurements of the stellar-mass deficits at the centers of luminous elliptical galaxies are presented. These were derived considering the following observational facts. First, "core" galaxies, which are thought to have had their inner region depleted from the coalescence of supermassive black holes, show an abrupt downward deviation of their inner light profile relative to their outer Sérsic profile. Second, "power-law" galaxies, having undisturbed profiles and no partially depleted core, have inner light profiles that display no departure from the inward extrapolation of their outer Sérsic profile. The central stellar deficits have therefore been derived from the difference in flux between the *Hubble Space Telescope* observed galaxy light profiles and the inward extrapolation of each galaxy's outer Sérsic profile. This approach gives flux deficits ∼0.1% of the total galaxy light and mass deficits that are ∼2 times each galaxy's central supermassive black hole mass. These results are in agreement with the theoretical expectations of mass ejection from binary black hole mergers and also with popular ΛCDM models of hierarchical galaxy formation. It is also explained why this result is some 10 times smaller than current observational estimates of the central mass deficit and therefore implies a merger history for giant elliptical galaxies that is 1 order of magnitude less violent than previously suggested.

Subject headings: black hole physics — galaxies: elliptical and lenticular, cD — galaxies: fundamental parameters

1. INTRODUCTION

The collisional construction of galaxies from the merger of lesser galaxies is thought to be a common occurrence in the universe. Coupled with the presence of a supermassive black hole (SMBH) at the heart of most galaxies (Kormendy & Richstone 1995; Magorrian et al. 1998; Richstone et al. 1998), dissipationless mergers have been proposed to explain the damaged nuclei in giant elliptical galaxies (e.g., Lauer et al. 1995; Faber et al. 1997; Rest et al. 2001). Although some galaxy "core depletion" is due to the SMBH(s) dining on stars that venture too close (e.g., Magorrian & Tremaine 1999; Zhao et al. 2002; Yu 2003), it is primarily from the gravitational slingshot effect that the coalescing SMBHs—from the premerged galaxies—have on stars while they themselves sink to the bottom of the potential well of the newly wed galaxy (Begelman et al. 1980; Ebisuzaki et al. 1991; Makino & Ebisuzaki 1996; Quinlan 1996; Quinlan & Hernquist 1997).

Theory predicts that the orbital decay of two such SMBHs should eject a core mass roughly equal to the combined black hole masses (Ebisuzaki et al. 1991; Milosavljević & Merritt 2001). Current measurements of the central stellar deficit are an order of magnitude larger than the central SMBH mass, suggesting that most elliptical galaxies have undergone multiple (≈8–10) major mergers (Milosavljević & Merritt 2001; Milosavljević et al. 2002; Ravindranath et al. 2002). This result, however, is at odds with popular models of hierarchical structure formation, which predict an average of only one (dissipationless) major-merger event for luminous elliptical galaxies (Haehnelt & Kauffmann 2002; Volonteri et al. 2003).

Recent advances in our understanding of galaxy structure have provided a new framework in which to think about, and measure, central mass deficits. It is now known that the "power-law" galaxies—understood not to have partially depleted cores, nor experienced a (major) dissipationless merger event—have an undisturbed Sérsic (1968) $R^{1/n}$ profile over their *entire* radial extent. That is, their inner light profiles show no deviation relative to their outer $R^{1/n}$ profile (Trujillo et al. 2004). On the other hand, the more luminous ($M_B < -20.5$ mag) "core" galaxies display a clear flattening of their inner light profile relative to the inward extrapolation of their outer Sérsic profile (Graham et al. 2003b, 2004; Graham & Guzmán 2003; Trujillo et al. 2004). The "break" in the profiles where this transition occurs marks the boundary of their relatively unpopulated cores.

In order to compute the central stellar deficit, and hence the level of damage to a galaxy's core, this Letter considers a pure Sérsic profile when representing the *original* stellar distribution of the disturbed profiles.

2. METHOD AND RESULTS

2.1. *Central Stellar Deficits*

We proceed by quantifying the central stellar deficit as the flux deficit relative to the inward extrapolation of the smoothly curving, stellar distribution outside of any possible, partially depleted core. This approach, therefore, does not assign *any* mass deficit to power-law galaxies, whose inner light profiles display no clear downward deviation from their outer Sérsic light profiles. Such a qualitative description can be placed on a quantitative footing through employment of the "core-Sérsic" light-profile model (Graham et al. 2003b), applied in Figure 1 to the core galaxy NGC 3348. This model consists of an inner power law and an outer Sérsic function. In practice (Trujillo et al. 2004), the transition at the "break radius" is sharp, providing a five-parameter function[2] capable of describing the entire radial extent of galaxies with cores.

The central flux deficit is obtained by differencing the lu-

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[2] The functional form of the complete core-Sérsic model can be seen in Graham et al. (2003b) and Trujillo et al. (2004).

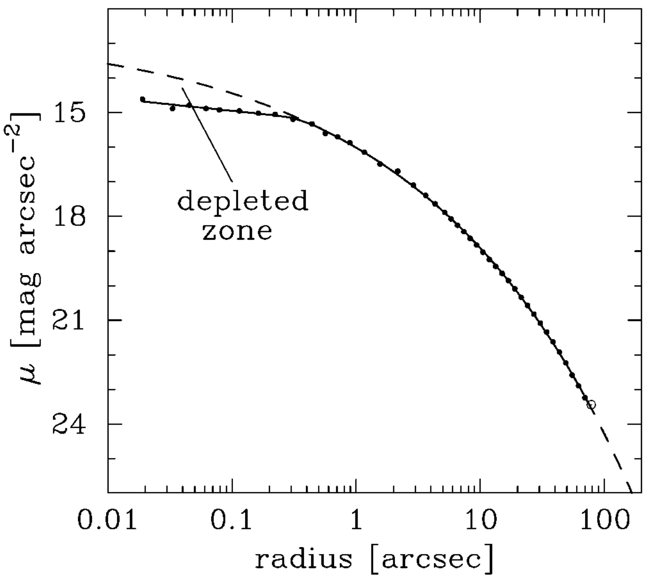

FIG. 1.—Observed, major-axis, R-band, surface brightness profile of NGC 3348. The solid line is the best-fitting core-Sérsic model, while the dashed line is the best-fitting Sérsic model to the data beyond the break radius $r_b = 0''.35$. The flux deficit is illustrated by the area designated as the "depleted zone," corresponding to a mass deficit of 300 million solar masses. Data points are from Trujillo et al. (2004) and supersede those shown in Graham et al. (2003b).

minosity $L(r) = \int_0^r 2\pi r I(r) dr$ within $r = r_b$ of (1) the inwardly extrapolated outer Sérsic profile

$$L_{\rm Ser}(r = r_b) = I_e r_e^2 2\pi n \frac{e^{b_n}}{(b_n)^{2n}} \Gamma_{\rm I}[2n,\ b_n(r_b/r_e)^{1/n}] \qquad (1)$$

and (2) a power-law light profile with slope γ matching the observed inner profile slope and intercepting the Sérsic model at $r = r_b$,

$$L_{\rm p\text{-}law}(r = r_b) = 2\pi r_b^2 I_b/(2 - \gamma). \qquad (2)$$

The term I_e is the intensity of the Sérsic profile at the effective radius r_e enclosing half the galaxy light. The exponent "$1/n$" describes the curvature of the light profile, and b_n is simply a function of n such that $\Gamma(2n) = 2\Gamma_{\rm I}(2n,\ b_n)$, where Γ and $\Gamma_{\rm I}$ are the complete and incomplete gamma functions, respectively. The intensity at r_b is denoted by I_b.

This procedure has been applied here to the seven bona fide core galaxies from Trujillo et al. (2004).[3] The resultant flux deficits are 0.07%–0.7% of the total galaxy flux. Allowing for the fact that these galaxies are at a range of distances from us, we converted the *apparent* magnitude differences $\Delta m(r = r_b) = -2.5 \log (L_{\rm Ser} - L_{\rm p\text{-}law})$ into *absolute* magnitudes (ΔM) using the galaxy distance estimates from Tonry et al. (2001) and then into units of solar flux using an absolute R-band magnitude for our Sun of $M_\odot = 4.46$ mag (Cox 2000). Finally, these values were transformed into solar masses assuming a stellar mass-to-light ratio of 3.0 (Worthey 1994). Such a ratio is representative of an evolved (i.e., faded) 12 billion year old, single stellar population observed through an R-band optical filter. The mass deficits $M_{\rm def}$ are given in Table 1.

2.2. *Constraints on the Number of Dry Mergers*

Models of hierarchical structure formation predict that galaxies will collide; indeed, this phenomenon has been observed for many years. Theoretical expectations for the ejected core mass, after the violent unification of galaxies containing SMBHs, scale as 0.5–$2NM_{\rm bh}$, where $M_{\rm bh}$ is the *final* black hole mass and N is the number of merger events (Milosavljević et al. 2002). The expectation that $M_{\rm def}$ scales with $NM_{\rm bh}$ assumes that (1) any preexisting core is preserved, that is, the already ejected core mass is not replenished in successive merger events, and (2) the clearing efficiency per unit SMBH mass remains constant from one merger event to the next. The variable term at the front is because equal-mass mergers scour out more stars than a collision involving a lesser mass, secondary galaxy. Thus, by knowing a galaxy's central stellar deficit (Table 1), and its black hole mass $M_{\rm bh}$, one can place constraints on the extent of this merger process.

[3] Clarifying note: The structural parameters tabulated in Trujillo et al. (2004) were obtained using the approximation $b_n \approx 1.999n - 0.3271$, and the r_e-values are for each galaxy's outer $R^{1/n}$ profile as if it had no partially depleted core.

TABLE 1
GALAXY DATA

			Core-Sérsic			Isothermal		Nuker	
Galaxy (1)	σ (km s^{-1}) (2)	$M_{\rm gal}$ (R mag) (3)	n (4)	r_b'' (pc) (5)	$M_{\rm def}$ (6)	r_b'' (pc) (7)	$M_{\rm def}$ (8)	r_b'' (pc) (9)	$M_{\rm def}$ (10)
NGC 2986	268	−22.49	5.28	0.69 (97)	7.02	2.9 (410)	35.5	1.24 (174)	26.7
NGC 3348	237	−22.76	3.81	0.35 (70)	3.01	2.5 (490)	66.1	0.99 (198)	26.5
NGC 4168	186	−21.92	3.12	0.72 (108)	1.21	8.3 (1250)	38.0	2.02 (303)	23.5
NGC 4291	284	−21.61	5.44	0.37 (47)	5.57	1.3 (170)	17.8	0.60 (076)	16.7
NGC 5557	253	−23.08	4.37	0.23 (51)	2.13	2.0 (440)	41.7	1.21 (269)	39.6
NGC 5903	210	−22.69	5.09	0.86 (141)	8.44	4.7 (780)	38.0	1.59 (262)	25.5
NGC 5982	250	−22.99	4.06	0.28 (57)	3.12	2.2 (450)	39.8	0.74 (151)	23.5

NOTES.—Col. (1): New General Catalog (NGC) numbers. Col. (2): Velocity dispersions σ from Hypercat (http://www-obs.univ-lyon1.fr/hypercat). Col. (3): Absolute R-band galaxy magnitudes $M_{\rm gal}$ derived from the best-fitting (sharp transition) core-Sérsic model; the parameters from which, including the Sérsic index n and the break radii r_b (in units of arcseconds and parsecs), can be found in Trujillo et al. (2004). Col. (6): The associated central mass deficits $M_{\rm def}$ (in units of $10^8\ M_\odot$) have been derived from the difference in flux between the observed light profile and the inward extrapolation of the outer Sérsic profile. The "isothermal" quantities have come directly from Milosavljević et al. (2002), who used the technique illustrated in Fig. 3*b*. The "Nuker" break radii have come from Rest et al. (2001), and the Nuker-derived mass deficits were obtained using eq. (41) from Milosavljević & Merritt (2001) with the required γ-values taken from Ravindranath et al. (2002).

We have estimated the SMBH mass of each galaxy using two techniques. First, we employed the $M_{\rm bh}$-σ relation of Gebhardt et al. (2000), in which $M_{\rm bh}$ is derived from the galaxy velocity dispersion σ. Using the steeper $M_{\rm bh}$-σ relation of Ferrarese & Merritt (2000) had little difference because of the different zero points in these two relations. The second SMBH mass estimate came from the independent $M_{\rm bh}$-n relation (Graham et al. 2001, 2003a). This relation is as strong as the $M_{\rm bh}$-σ relation and has the same small degree of scatter, but has the advantage that it is a purely photometric technique, requiring only (uncalibrated) images rather than (telescope-time expensive) galaxy spectra. Figure 2 shows each galaxy's depleted core mass plotted against both estimates of the SMBH mass. The ratio of the stellar mass deficit to central black hole mass has a mean $\pm$ average deviation of 2.4 ± 0.7 (Fig. 2*a*, $M_{\rm bh}$-n) and 2.1 ± 1.1 (Fig. 2*b*, $M_{\rm bh}$-σ), consistent with these galaxies having experienced one major (i.e., equal-mass) dry merger event.

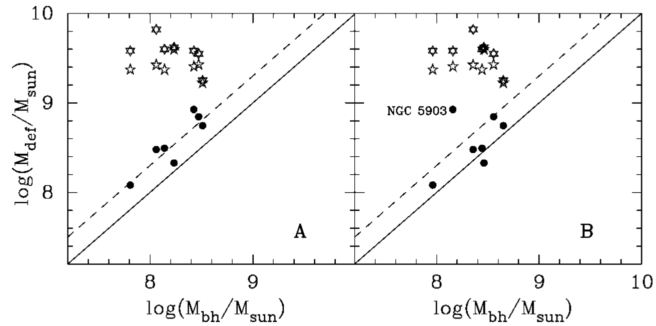

FIG. 2.—Central mass deficits evaluated from three techniques vs. the central black hole masses derived using (*a*) the galaxy Sérsic index n (Graham et al. 2001, 2003a) and (*b*) the velocity dispersion σ (Gebhardt et al. 2000). Hexagons are from Milosavljević et al. (2002) using the method illustrated in Fig. 3*b*. Star symbols are derived using Nuker-model break-radii and eq. (41) from Milosavljević & Merritt (2001). Filled circles are derived here using the logic illustrated in Fig. 1. The solid line shows a one-to-one relation; the dashed line shows $M_{\rm def} = 2M_{\rm bh}$. Typical errors for the points marked with a filled circle are roughly log 2 along both axes, stemming from a ~20% and ~15% uncertainty on the value of n and σ, respectively, and from profile fitting and galaxy distance uncertainties.

3. DISCUSSION

Support for the above mass deficits comes from the agreement with the merger simulations of Makino & Ebisuzaki (1996), the (cusp regeneration) hierarchial merger models of Volonteri et al. (2003), and the theoretical expectations of Haehnelt & Kauffmann (2002). Although the latter authors predicted a median number of equal-mass mergers for faint (power law) and bright (core) elliptical galaxies of one and three, respectively, the number of major mergers since the last collision that involved substantial gas accretion ($M_{\rm gas} > M_{\rm bh}$) is zero and one, respectively. The presence of gas is important because it dilutes the wrecking ball action of the SMBHs on the stars because it, rather than the stars, fosters the coalescence of the black holes and it can lead to the creation of new stars (see, e.g., Zhao et al. 2002 and references therein). Therefore, our conclusions that power-law galaxies do not have partially depleted cores from galaxy collisions, and that the number of (dissipationless) major mergers producing luminous galaxies, with $M_R \sim -22.5$ mag, is equal to about one, are supported by current cold dark matter models of hierarchial structure formation.

Given $M_{\rm def} \sim M_{\rm bh}$, one may wonder if some depleted cores might have formed from the runaway merging of stars (e.g., Begelman & Rees 1978; Quinlan & Shapiro 1989) within what may once have been the dense cores of massive elliptical galaxies (Graham & Guzmán 2003), rather than from the scattering of stars from coalescing black holes. The first objection to such a process would be those cases in which $M_{\rm def}$ is actually greater than $M_{\rm bh}$. Such a mechanism would also require a certain level of refinement, such as repopulating the loss cone, in order to explain the absence of (resolved) cores in less luminous elliptical galaxies. The expected break radii—derived from a centrally depleted Sérsic model—are not observed among the power-law galaxies. For example, if the 12 power-law galaxies in Trujillo et al. (2004) had cores with inner power-law slopes ranging from 0.0 to 0.3, then, assuming $M_{\rm def} = M_{\rm bh}$, they should have break radii of 0″.17–0″.5, which they do not.

It is pertinent to inquire why previous estimates of the central mass deficit are larger than the values obtained here. One reason is that it had been assumed that every galaxy once had a steep isothermal $\rho(r) \sim r^{-2}$ core before any merging black holes wreaked their havoc. There is, however, no observational evidence that any such universal density profile $\rho(r)$ exists or once existed among the power-law galaxies. In actuality, a luminosity-dependent range of inner profile shapes is now known to exist (Gebhardt et al. 1996; Graham & Guzmán 2003; Balcells et al. 2004). No single power-law slope can be used to approximate the initial, undisturbed, stellar distribution of all elliptical galaxies.

Milosavljević et al. (2002), for example, had defined the onset of partially depleted cores as the radius where the negative, logarithmic gradient of the deprojected light profiles (i.e., the spatial, luminosity-density profiles) equaled 2, that is, where the observed slope matched that of the isothermal model. They then derived central, stellar mass deficits from the difference between the observed density profile and the inward extrapolation of the isothermal model from this point. This approach to estimating the depleted core mass is illustrated in Figure 3, where we show both the observed light profile and the (deprojected) density profile of the coreless, power-law galaxy NGC 5831. Such a prescription encounters a number of difficulties. An extraordinary degree of fine-tuning would be required to deplete stars over the full radial extent of the initial isothermal core, assuming one existed, but not beyond the core radius, which one assumes still has its original slope of -2 today. Moreover, with such an approach, many of the power-law galaxies that are not (traditionally) recognized as having a partially depleted core will be assigned one. Such theoretical core radii (and mass deficits) are not only questionable but excessively large—sometimes greater than 1 kpc—and do not match the observed break radii in core galaxies, which are invariably less than a few hundred parsecs (see Table 1).

A second approach to estimating the central deficit had been to use break radii derived from the Nuker model (Lauer et al. 1995) and to assume an isothermal core once existed inside of this radius. With such an approach, the estimated central deficits are again too high because of (1) the excessively steep isothermal model that is assumed and (2) because, as described in Graham et al. (2003b) and shown in Trujillo et al. (2004), Nuker-derived break radii typically overestimate the actual break radii by factors of 2–5.

The mass deficits obtained with the above two methods are 3–30 times larger than our values and are shown in Figure 2 for comparison. Our new measurements of the mass deficit are significantly (99.4%, from both a Kolmogorov-Smirnov test and Student's t-test) different from those values obtained using

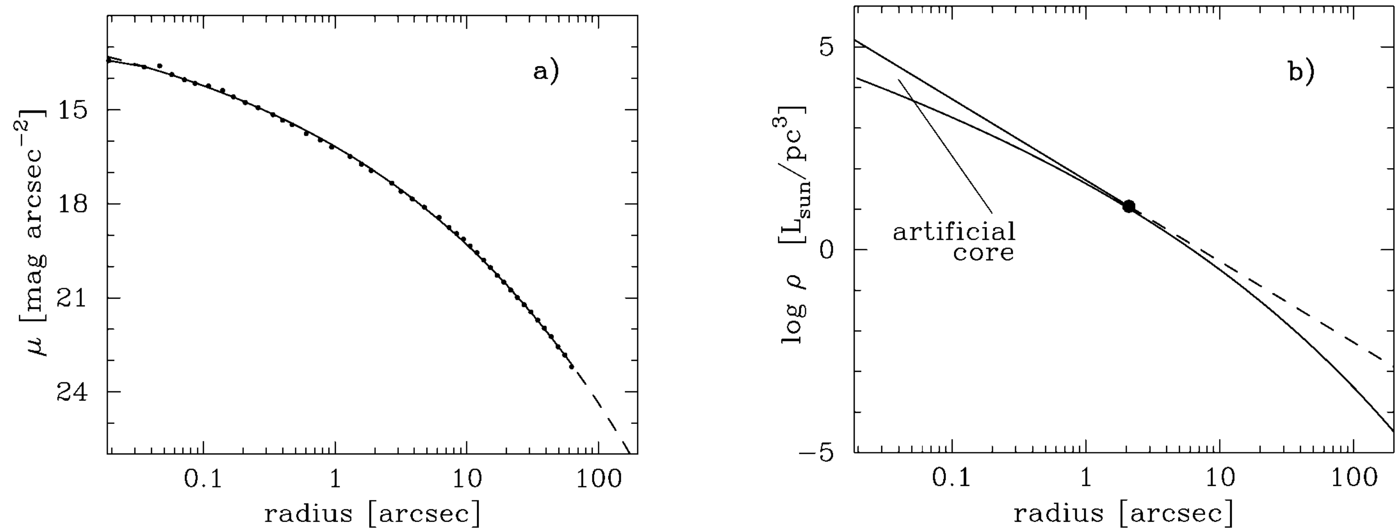

FIG. 3.—(*a*) Observed, major-axis, *R*-band, surface brightness profile of the coreless galaxy NGC 5831 (data taken from Trujillo et al. 2004). A three-parameter Sérsic model (*solid line*) adequately describes the stellar distribution on both the nuclear ($\lesssim 1''$) and global scale; the dashed line shows the model extrapolated beyond the data. No characteristic downward break in the inner light profile, which would signify damage caused by merging SMBHs, is evident. (*b*) Spatial density profile (*curved line*) of NGC 5831 obtained by deprojecting the light-profile model in panel *a*. Assuming an isothermal model, $\rho(r) \sim r^{-2}$, once existed (*straight line*), one can assign a theoretical core radius r_b—where the logarithmic density profile has a slope of -2—and a central mass deficit. Milosavljević et al. (2002) obtained $r_b = 220$ pc and $M_{\rm def} = 5.6 \times 10^8\ M_\odot$.

the isothermal assumption and reveal that the galactic merger history of the universe, at least for massive elliptical galaxies, is roughly an order of magnitude less violent than previous observational analyses (Milosavljević & Merritt 2001; Milosavljević et al. 2002; Ravindranath et al. 2002) had suggested.

We plan on analyzing more galaxies and measuring the ellipticity of their evacuated core region. This may shed light on the orientation of the initial orbits of the black holes and allow one to explore any possible correlation with the host galaxy ellipticity. A greater range of data will also allow one to explore whether there is any trend between $M_{\rm def}/M_{\rm bh}$ and galaxy magnitude. Such a correlation may be expected if bigger core galaxies have experienced more dissipationless merger events than less luminous core galaxies.

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