THE FORMATION OF GALAXY STELLAR CORES BY THE HIERARCHICAL MERGING OF SUPERMASSIVE BLACK HOLES

MARTA VOLONTERI, 1 PIERO MADAU, 1 AND FRANCESCO HAARDT 2

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ABSTRACT

We investigate a hierarchical structure formation scenario in which galaxy stellar cores are created from the binding energy liberated by shrinking supermassive black hole (SMBH) binaries. The binary orbital decay heats the surrounding stars, eroding a preexisting stellar cusp \( r^{-2} \). We follow the merger history of dark matter halos and associated SMBHs via cosmological Monte Carlo realizations of the merger hierarchy from early times to the present in an LCDM cosmology. Massive black holes get incorporated through a series of mergers into larger and larger halos, sink to the center through dynamical friction, accrete a fraction of the gas in the merger remnant to become supermassive, and form a binary system. Stellar dynamical processes drive the binary to harden and eventually coalesce. A simple scheme is applied in which the loss cone is constantly refilled and a constant density core forms because of the ejection of stellar mass. We find that a model in which the effect of the hierarchy of SMBH interactions is cumulative and cores are preserved during galaxy mergers produces at the present epoch a correlation between the “mass deficit” (the mass needed to bring a flat inner density profile to a \( r^{-2} \) cusp) and the mass of the nuclear SMBH, with a normalization and slope comparable to the observed relation. Models in which the mass displaced by the SMBH binary is replenished after every major galaxy merger appear instead to underestimate the mass deficit observed in “core” galaxies.

Subject headings: black hole physics — cosmology: theory — galaxies: evolution — quasars: general

1. INTRODUCTION

The strong link observed between the masses of supermassive black holes (SMBHs) residing at the center of most nearby galaxies and the gravitational potential wells that host them (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Ferrarese 2002) suggests a fundamental mechanism for assembling black holes (BHs) and forming spheroids in galaxy halos. In popular cold dark matter (CDM) “bottom-up” cosmologies, the host galaxies of SMBHs experience multiple mergers during their lifetime (Kauffmann & Haehnelt 2000; Menou, Haiman, & Narayanan 2001), with those between comparable-mass systems (“major mergers”) expected to result in the formation of elliptical galaxies (Barnes 1988). If the hierarchical buildup of SMBHs traces far up in the dark halo merger tree, binary BH systems may be widespread (Volonteri, Haardt, & Madau 2003, hereafter Paper I). As galaxies hosting nuclear BHs merge, the holes will sink to the center of the merger remnant, because of dynamical friction from field particles, and form a bound pair.

If was first proposed by Ebisuzaki, Makino, & Okumura (1991) that the heating of the surrounding stars by a decaying SMBH pair would create a low-density core out of a preexisting cuspy stellar profile. In a stellar background a “hard” binary shrinks by capturing the stars that pass close to the holes and ejecting them at much higher velocities, a superelastic scattering process that depletes the nuclear region. Rapid coalescence eventually ensues because of the emission of gravitational radiation. Observationally, there is clear evidence in early-type galaxies for a systematically different distribution of surface brightness profiles, with faint ellipticals showing steep power-law profiles (cusps), while bright ellipticals have much shallower stellar cores (Lauer et al. 1995; Gebhardt et al. 1996; Faber et al. 1997; Ravindranath et al. 2001). “Core” galaxies have high velocity dispersions and exhibit a definite break in the brightness profile at some radius that scales with luminosity as \( \propto L^{1.13} \) (Faber et al. 1997). Detailed N-body simulations have confirmed the cusp-disruption effect of a hardening BH binary (Makino & Ebisuzaki 1996; Quinlan & Hernquist 1997; Milosavljevic & Merritt 2001), but have shed little light on why bright ellipticals have lower central concentrations than do faint ellipticals.

The role of binaries in shaping the central structure of galaxies can be best understood within the framework of a detailed model for the hierarchical assembly of SMBHs over cosmic history (Paper I; Haehnelt & Kauffmann 2002), particularly if the damage done to a stellar cusps by decaying BH pairs is cumulative and nuclear cores are preserved during galaxy mergers. In this paper we study the effects of hierarchical mergers of halo+SMBH systems on the inner density profiles of galaxies using the machinery for following the growth and dynamics of SMBHs developed in Paper I. We show that stellar cusps can be efficiently destroyed over cosmic time by decaying SMBH binaries if stellar dynamical processes are able to shrink the binary down to a separation \( \lesssim 10\% \) of the separation at which the binary becomes hard. More massive halos have more massive nuclear BHs and experience more merging events than less massive galaxies: hence they suffer more from the eroding action of binary SMBHs and have larger cores.

2. ASSEMBLY AND GROWTH OF SMBHs

We briefly summarize here the main features of our scenario for the hierarchical growth of SMBHS in a \( \Lambda CDM \)
cosmology (see Paper I for a thorough discussion). The merger history of 220 parent halos with present-day masses in the range $10^{11} M_\odot < M_0 < 10^{13} M_\odot$ is tracked backward with a Monte Carlo algorithm based on the extended Press-Schechter formalism. Compared to Paper I, we use an improved version in which the most massive halos are broken up into as many as 280,000 progenitors by $z = 20$. We adopt a two-component model for galaxy halos. The dark matter is distributed according to an NFW profile (Navarro, Frenk, & White 1997),

$$\rho_{DM}(r) = \frac{M}{4\pi r (r + r_{\text{vir}}/c) f(c)},$$

where $r_{\text{vir}}$ is the virial radius, $c$ is the halo concentration parameter, and

$$f(c) = \ln(1 + c) - \frac{c}{1 + c}.$$  

Following Bullock et al. (2001), the mean concentration is assumed to scale with halo mass $M$ and redshift of collapse $z$ as

$$c = \frac{9}{1 + z} \left( \frac{M}{8 \times 10^{12} h M_\odot} \right)^{-0.14}.$$  

Individual halos have a lognormal distribution with dispersion about the mean $\Delta(\log c) = 0.18$. During the merger of two halo+BH systems of comparable masses, dynamical friction against the dark matter background drags in the satellite hole toward the center of the newly merged system, leading to the formation of a bound BH binary in the violently relaxed stellar core. The dynamical friction timescale depends on the orbital parameters of the infalling satellite, which we take from van den Bosch et al. (1999). At late epochs, most of the BH pairs have unequal masses, with mass ratios ranging between 10% and 20% (Paper I).

The subsequent evolution of the binary is determined by the initial central stellar distribution. We model this as a singular isothermal sphere (SIS) with one-dimensional velocity dispersion $\sigma_*$. The stellar velocity dispersion is related to the halo circular velocity $V_c$ at the virial radius following Ferrarese (2002),

$$\log V_c = (0.88 \pm 0.17) \log \sigma_* + (0.47 \pm 0.35).$$

We truncate the stellar SIS at $0.16 r_{\text{vir}}$ in order for the total stellar mass fraction to equal the universal baryon fraction, $\Omega_b/\Omega_M$. In our model pregalactic “seed” holes form with intermediate masses ($m_s = 150 M_\odot$) in (mini)halos collapsing at $z = 20$ from rare 3.5 $\sigma$ peaks of the primordial density field (Paper I; Madau & Rees 2001). The assumed “bias” assures that almost all halos above $10^{11} M_\odot$ actually host a BH at all epochs. We found little change in the $z < 5$ results in a test model case with $m_s = 1000 M_\odot$. In each major merger the more massive hole accretes at the Eddington rate a gas mass that scales with the fifth power of the circular velocity of the host halo,

$$\Delta m_{\text{acc}} = 3.6 \times 10^6 M_\odot \mathcal{H} V_{c,150}^{5.2},$$

where $V_{c,150}$ is the circular velocity of the merged system in units of 150 km s$^{-1}$. The normalization is fixed a posteriori in order to reproduce the observed local $m_{\text{BH}} - \sigma_*$ relation (Ferrarese 2002). The present-day mass density of nuclear SMBHs accumulates mainly via gas accretion, with BH-BH mergers playing only a secondary role. This model was shown in Paper I to reproduce remarkably well the observed luminosity function of optically selected quasars in the redshift range $1 < z < 5$.

If the merging timescales of SMBH binaries are longer than the characteristic timescale between major galaxy mergers, then interactions between the binary and new infalling holes will be likely. In Paper I we discussed a scenario in which binaries decay efficiently both as a result of mass ejection from a cuspy stellar density profiles and, at very high redshifts, because of triple BH interactions. In the next section we expand upon Paper I and describe a scheme for generating low-density cores out of a preexisting stellar cusps from the binding energy liberated by shrinking SMBH binaries.

### 3. Dynamical Evolution of SMBH Binaries

Consider a binary with BH masses $m_1 \geq m_2$ and semimajor axis $a(t)$ in an isotropic background of stars of mass $m_\star < m_2$ and density $\rho_\star(r)$. The binary will initially shrink by dynamical friction from distant stars acting on each BH individually. But as the binary separation decays, the effectiveness of dynamical friction slowly declines because distant encounters perturb only the binary center of mass but not its semimajor axis. The BH pair then hardens via three-body interactions, i.e., by capturing and ejecting at much higher velocities the stars passing by within a distance $\sim a$ (“gravitational slingshot”). The system becomes hard when the value of $a$ falls below

$$a_h = \frac{G m_2}{4 \pi \sigma_*^3 (1 + \gamma)},$$

(Quinlan 1996). We assume that the “bottleneck” stages of the (bound) binary shrinking occur for separations $a < a_h$; during a galactic merger, after a dynamical friction timescale, we place the BH pair at $a_h$ and let it evolve.

The hardening of the binary modifies the stellar density profile, removing mass interior to the binary orbit, depleting the galaxy core of stars, and slowing down further hardening. If $\dot{m}_{\text{ej}}$ is the stellar mass ejected by the BH pair, the binary evolution and its effect on the galaxy core are determined by two dimensionless quantities: the hardening rate

$$H = \frac{\sigma_*^3 d}{G \rho_\star \Delta t a},$$

and the mass ejection rate

$$J = \frac{1}{m_1 + m_2} \frac{d \dot{m}_{\text{ej}}}{d \ln(1/a)}.$$
scattering experiments that treat the star-binary encounters one at a time. Following Quinlan (1996), we take \( H = 15 \) independent of \( a \) (for \( a < a_0 \)) and of the binary mass ratio. The quantity \( J \) is instead a function of binary separation and has some dependence on \( m_1/m_2 \). We interpolate/extrapolate Quinlan’s numerical results to obtain \( J(a) \) for different mass ratios (cf. Paper I). The merger timescale is computed adopting a simple semianalytical scheme that qualitatively reproduces the evolution observed in \( N \)-body simulations (Merritt 2000; Paper I). We assume that the stellar mass removal creates a core of radius \( r_c \) and constant density \( \rho_c \equiv \rho_s (r_c) \), so that the total mass ejected as the binary shrinks from \( a_0 \) to \( a \) can be written as

\[
M_{ej} = \frac{2\pi G}{3} \left( \frac{r_c - r_i}{a} \right) + M_i - M_c = \frac{4}{3} \frac{\sigma_s^3 (r_c - r_i)}{G} \, ,
\]

where \( M_i = 4\pi \rho_i r_i^3/3 \), \( M_c = 4\pi \rho_c r_c^3/3 \), \( r_i = r_i(t=0) \) is the radius of the (preexisting) core when the hardening phase starts at \( t = 0 \), and \( \rho_i \equiv \rho_s (r_i) \). The core radius then grows as

\[
r_c(t) = r_i + \frac{3}{4\pi \rho_s} \frac{G(m_1 + m_2)}{H \sigma_s} \int_{a(t)}^{a} \frac{J(a)}{a} \, da \, .
\]

The binary separation quickly falls below \( r_c \) and subsequent evolution is slowed down because of the declining stellar density, with a hardening time,

\[
t_h = \left\{ \frac{a}{\dot{a}} \right\} = \frac{2\pi r_c(t)^2}{H \sigma_s a} \, ,
\]

that becomes increasingly long as the binary shrinks. The mass ejected increases approximately logarithmically with time, and the binary “heats” background stars at radii \( r_c > a \). If the hardening continues sufficiently far, gravitational radiation losses finally take over, and the two BHs coalesce in less than a Hubble time. If the scheme for core creation investigated here, at all redshifts \( z < 5 \) the binary hardening timescale is always less than the time it takes the “satellite” halo+BH system to sink to the center of the more massive progenitor because of dynamical friction against the dark matter background.

The above relations assume that the stellar velocity dispersion remains constant during the hardening of the binary. This is a reasonable assumption, as the two-body stellar relaxation timescale

\[
t_r = 0.34 \frac{\sigma_s^3}{G^2 m_s \rho_s \ln \Lambda} = 7 \, \text{Gyr} \left( \frac{r_c}{\text{pc}} \right)^2 \left( \frac{10}{\ln \Lambda} \right) \sigma_{150} \]

is typically much longer than the hardening time. Here \( \Lambda \) is of order the total number of stars, \( m_s \) is the typical stellar mass, and \( \sigma_{150} \) is the stellar velocity dispersion in units of 150 km s\(^{-1}\). More importantly, we have neglected the depopulation of the loss cone, since it is the total stellar density that is allowed to decrease following equation (11), not the density of low angular momentum stars. The effect of loss-cone depletion (the depletion of low angular momentum stars that get close enough to extract energy from a hard binary) is one of the major uncertainties in computing the merger timescale, and makes it difficult to construct viable merger scenarios for BH binaries. The wandering of the binary center of mass from the galaxy center induced by continuous interactions with background stars (Quinlan & Hernquist 1997), the large supply of low angular momentum stars in significantly flattened or triaxial galaxies (Yu 2002), the presence of a third BH (Valtonen et al. 1994; Blaes, Lee, & Socrates 2002; Paper I), the loss of orbital angular momentum to a gaseous disk (Gould & Rix 2000; Armitage & Narayan 2002), and the randomization of stellar orbits due to the infall of small satellites (Zhao, Haehnelt, & Rees 2001) will all mitigate to some extent the problems associated with loss-cone depletion (which may ultimately cause the binary to stall) and help the binary merge.

4. RESULTS

The ability of SMBH binaries in shaping the central structure of galaxies depends not only on the efficiency of three-body interactions at hardening the binary but also on how galaxy mergers affect the inner stellar density profiles, i.e., on whether cores are preserved or steep cusps are regenerated during major mergers. To bracket the uncertainties and explore different scenarios we run three different sets of Monte Carlo realizations. In the first (“cusp regeneration”) we assume, as in Paper I, that the stellar cusp \( \propto r^{-2} \) is promptly regenerated after every major merger event, i.e., we replenish the mass displaced by the binary and reset \( r_i = 0 \) after every major merger. In the second (“core preservation”) the effect of the hierarchy of SMBH binary interactions is instead cumulative, i.e., \( r_i \) is allowed to grow continuously during the cosmic evolution of the host. This second model is supported by \( N \)-body simulations involving mergers of spherical galaxy models with different density profiles, and showing that the remnant profile is quite close to the profile of the progenitors—in other words, that the core appears to be preserved during such mergers (e.g., Fulton & Barnes 2001). The third set is similar to the second, except that stellar ejection is switched off at separation \( a = 0.1 a_0 \), as may be expected in the case the depletion of the loss cone were to “stall” the binary around that separation (e.g., Milosavljevic & Merritt 2002). Thereafter the binary is assumed to shrink rapidly because of (say) gas processes and coalesce. As shown below, this case yields results that are intermediate between the first two.

Let us focus on the first two sets of realizations. Figure 1 shows how the mean core radius grows as a function of redshift in the simulated merger history of a \( M_0 = 2 \times 10^{12} M_\odot \) and \( M_0 = 10^{13} M_\odot \) halo. The cores created by shrinking SMBH binaries tend to remain small \((r_c < 1 \, \text{pc})\) until relatively recent times: on average, core radii approximately double between \( z = 1 \) and the present epoch. Core radii are also twice as large in the core preservation case than in the cusp regeneration one. (Note that in the latter averaging over all realizations smoothes out the \( r_i = 0 \) resetting after every major merger event.)

Because of the lower central densities, binaries that form in the mergers of massive galaxies decay much less rapidly in the model that preserves cores than in the one in which cusps are regenerated. Figure 2 shows the expected mean core radius at \( z = 0 \) as a function of halo mass. Small galaxies have tiny cores or no core at all, while massive galaxies have core radii that can exceed hundreds of parsecs.
of BH seeds with respect to the mean at early epochs, and some of them never host binaries. By contrast, more massive galaxies form through the merging of an above-average number of primordial high-$\sigma$ minihalos, and so the damage done by shrinking BH binaries is enhanced. Note that, in the case of core preservation, the core radius is typically $\sim 3$ times larger than the radius of the “sphere of influence” of the final SMBH, $r_{\text{BH}} = Gm_{\text{BH}}/\sigma_{\star}^2$. The predicted $r_c$ of the most massive halos in the core preservation case is larger than the core one would simply compute from equation (11) assuming $r_c = 0$, an equal mass BH merger ($m_1 = m_2$), and a final merged BH mass that satisfies the $m_{\text{BH}} - \sigma_{\star}$ relation of Ferrarese (2002), $r_c \propto m_{\text{BH}}/\sigma_{\star}^2 \propto m_{\text{BH}}^{5/7}$.

How do our results compare with observations? The simple models for core creation described above yields core radii that scale almost linearly with galaxy mass, $r_c \propto M_{\odot}^{0.8} - M_{\odot}^{0.9}$ in the range $10^{12} M_{\odot} < M_{\odot} < 4 \times 10^{13} M_{\odot}$. A similarly scaling relation was observed by Faber et al. (1997). Our core sizes, however, are sensitive to the adopted density profile. We have assumed here that the continuous eroding action of shrinking binaries generates a flat density core. In the simulations of Milosavljevic & Merritt (2001), mergers of equal-mass stellar systems containing SMBHs and steep central density cusps produce nuclei with shallower cusps $\propto r^{-1}$ rather than flat cores. Observationally, even core galaxies exhibit very shallow power-law density profiles. A better test of our model predictions against galaxy data is provided by the “mass deficit,” i.e., the mass in stars that must be added to the observed cores to produce a stellar $r^{-2}$ cusp. Milosavljevic et al. (2002) (see also Rавин-драранат, Ho, & Filippenko 2002) have recently shown that the mass deficit inferred in a sample of early-type core galaxies correlates well with the mass of their nuclear black holes, consistent with the prediction of coalescing SMBH binary models. In our model this quantity,

$$M_{\text{def}} = \frac{4\sigma_{\star}^2 r_c}{3G},$$

is proportional to the total stellar mass ejected by shrinking binaries over cosmic history, and is directly related to the hardening efficiency.

Figure 3 compares the mass deficit inferred from the data with the same quantity found at $z = 0$ in our merger tree,

$$\frac{M_{\text{def}}}{M_{\odot}} = (8.2 \pm 3.8) \left(\frac{m_{\text{BH}}}{M_{\odot}}\right)^{0.98 \pm 0.03},$$

(core preservation) and

$$\frac{M_{\text{def}}}{M_{\odot}} = (11.5 \pm 4.2) \left(\frac{m_{\text{BH}}}{M_{\odot}}\right)^{0.93 \pm 0.02}$$

(cusp regeneration), where the fit was performed in the same $m_{\text{BH}}$ range of the observations. The cusp regeneration case predicts $M_{\text{def}} \simeq 2.7m_{\text{BH}}$ for $m_{\text{BH}} = 10^9 M_{\odot}$, and clearly underestimates the mass deficit observed in massive core galaxies, $\langle M_{\text{def}}\rangle \simeq 10m_{\text{BH}}$. We find that typically about half of $M_{\text{def}}$ is generated in the last binary merger. Note that the mass deficit defined in this way is about 25% larger than the stellar mass physically ejected in our simulations, since in our scheme $\sigma_{\star}$ (hence the mass deficit) keeps increasing after

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**Fig. 1.**—Mean (averaged over 20 realizations) core radius of the main halo of the merger tree as a function of redshift. The expansion of the core is supported by the binding energy liberated by shrinking SMBH binaries. Solid line: $M_0 = 2 \times 10^{12} M_{\odot}$ halo. Dashed line: $M_0 = 10^{13} M_{\odot}$ halo. Left panel: cusp regeneration case. Right panel: core preservation case.

This is due to two effects: (1) our accretion recipe is fixed in order to reproduce the observed local $m_{\text{BH}} - \sigma_{\star}$ relation. More massive halos have more massive central SMBHs and hence larger cores; and (2) the assumed “bias” in the frequency of primordial seed BHs. Low-mass galaxies today are “anti-biased” as they are assigned a smaller abundance

**Fig. 2.**—Mean core radius as a function of halo mass. Error bars are 1 $\sigma$ rms. Lower filled circles: cusp regeneration case. Upper filled circles: core preservation case. Dashed line: core radius computed from eq. (11) assuming $r_c = 0$, an equal mass BH binary ($m_1 = m_2$), and a final merged BH mass that satisfies the $m_{\text{BH}} - \sigma_{\star}$ relation. Note that this prescription overpredicts $r_c$ at low masses: this is due to small SMBHs deviating in our model from the extrapolated $m_{\text{BH}} - \sigma_{\star}$ relation.

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5 More precisely, the mass deficit is defined as the difference in integrated mass between the deprojected density profile and a $r^{-2}$ cusp extrapolated inward from the break radius.
binary coalescence as a consequence of the accretion of small dark matter satellites along the merger tree.

The predicted $M_{\text{def}}-m_{\text{BH}}$ correlation is too tight compared to the observations: a distribution of inner density profiles before and after galaxies merge and observational errors may both contribute to the large scatter in the data points. We also draw attention to the fact that the mass deficits estimated for the cuspy galaxies of Faber et al. (1997) should be strictly considered as upper limits, and the observed $M_{\text{def}}-m_{\text{BH}}$ relation may then be steeper than predicted (see also Ravindranath et al. 2002). A few galaxies in the sample of Faber et al. have cores significantly smaller than expected from their central BH mass (e.g., NGC 3115, with a break radius $\sim 2$ pc and $m_{\text{BH}} = 10^9 M_\odot$). Similarly, the Milky Way galaxy has a BH with $m_{\text{BH}} = 3 \times 10^6 M_\odot$ and a stellar core radius $r_c = 0.38$ pc (Genzel et al. 2000). Within our simple scheme, objects with these properties are very rare in the core preservation case, and may require some form of cusp regeneration mechanism.

The mass deficit measured in our third set of realizations is depicted in Figure 4. This assumes core preservation and switches off stellar ejection when $a = 0.1 a_0$, i.e., stellar dynamical processes become inefficient at small binary separations. Even in this scenario stellar cusps may be efficiently destroyed over cosmic time by decaying SMBH binaries: the expected mass deficit is less than a factor of 2 smaller than in the standard core preservation case.

5. DISCUSSION

We have assessed a hierarchical structure formation scenario in which galaxy inner cores are created from the binding energy liberated by shrinking SMBH binaries. The binary orbital decay heats the surrounding stars, eroding a preexisting stellar cusp $\propto r^{-2}$. A simple model in which the effect of the hierarchy of SMBH interactions is cumulative produces a correlation between “mass deficit” and the mass of nuclear SMBHs with a normalization and slope that are comparable to the observed relation. This model is also able to reproduce the observed scaling relation between galaxy luminosity and core size. Relating the dark halo mass to galaxy luminosity using the mass-to-light ratios of van den Bosch, Mo, & Yang (2003), we find $r_c \propto L_{\text{g}}^{1/2}$ in the mass range $10^{12} M_\odot < M_\odot < 4 \times 10^{13} M_\odot$, in agreement with the scaling observed by Faber et al. (1997). Despite these encouraging results, models of core formation by binary SMBHs remain uncertain. The ability of SMBH binaries in modifying the inner density profiles of galaxies depends on whether cores are preserved or steep cusps are regenerated during galaxy mergers, and on the poorly known efficiency of three-body interactions at hardening the binary.

There are of course further complications.

1. If the age of the stellar core+BH system is much larger than the local relaxation time, then an equilibrium distribution of bound stars will be set up within the BH sphere of influence. We find that such a steady-state density cusp, $\rho_s \propto r^{-7/4}$ (Bahcall & Wolf 1976; Peebles 1972; Frank & Rees 1976; Lightman & Shapiro 1977) will have no time to develop in our hierarchical scheme for the assembly of SMBHs, as the relaxation timescales are typically rather long. If the age of the system is instead much less than the relaxation time, and the hole grows by accreting gas on a timescale that is long compared with the orbital period of the surrounding stars, then again a power-law density cusp will be created, this time with slope $r^{-3/2}$ extending to $r_{\text{BH}}$ (Young 1980). As the mass of the hole increases, the core will start to loose its identity until, when $r_{\text{BH}} > r_c$, the cusp
will join smoothly onto the $r^{-2}$ isothermal profile. Adiabatic growth of stellar cusps is typically not important within our scheme, since we find that the core mass $M_c$ exceeds $m_{\text{BH}}$, i.e., that $r_{\text{BH}} < r_c$ in most systems.

2. Dark matter particles will be ejected by shrinking SMBH binaries in the same way as the stars, i.e., through the gravitational slingshot. Their contribution to binary hardening will be weighted by the fraction $f_{\text{DM}} = \rho_{\text{DM}} / (\rho_{\text{DM}} + \rho_{\text{s}})$, typically $\ll 1$ in galaxy cores for our assumed density distributions. The NFW profile is shallower than the SIS profile in the inner regions, so ejection of a given mass will create a larger core in an NFW profile. The mass ejected in dark matter is, however, significantly less than the mass ejected in stars. Eventually, the destruction of dark matter cusps by binary SMBHs may lead to cores of the same extent as the stellar ones. Furthermore, the erosion of the stellar cusp may lower the central dark matter density through a process (“adiabatic expansion”) that is the opposite of the adiabatic compression of dark halos in response to baryonic cooling and infall (Blumenthal et al. 1986). While the observed rotation curves of dwarf and lower surface brightness galaxies suggest that the inner regions have constant density cores rather than the density cusps predicted by CDM (McGaugh & De Blok 1998; Swaters et al. 2003), shrinking BH binaries will not alleviate significantly this “CDM cusp problem,” since the predicted mass deficit is much lower than that required to fit the rotation curves.

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