Abstract. We present the results of N-body simulations of the accretion of high-density dwarf galaxies by low-density giant galaxies. Both galaxies contain power-law central density cusps and point masses representing supermassive black holes; the ratio of galaxy masses is 3 : 1. The cusp of the dwarf galaxy is always disrupted during the merger, leading to a remnant with a weak power law in the intrinsic density and a “core” in the projected density. Removing both black holes from the giant and dwarf galaxies allows the dwarf galaxy to remain intact and leads to a remnant with a high central density, contrary to what is observed. Our results support the hypothesis that the persistence of low-density cores in giant galaxies following mergers is a consequence of the existence of supermassive central black holes.

1. Introduction

Bright elliptical galaxies and bulges of spiral galaxies tend to be less dense than faint galaxies. The luminosity density in the central regions of these galaxies rises approximately as a power law at the smallest observable radii, $\rho \sim r^{-\gamma}$. Faint galaxies ($M_V \gtrsim -20$) have $1.5 \lesssim \gamma \lesssim 2.5$ while bright galaxies have $0 \lesssim \gamma \lesssim 1.5$ (Ferrarese et al. 1994; Gebhardt et al. 1996). There are some interesting questions relating to these observed facts: (1) How did the cusps form? (2) How are the weak cusps in bright galaxies maintained in spite of mergers with dense low-luminosity galaxies? If the small galaxy survived such a merger with its central regions intact, this would create a new high-density core in the center of the big galaxy and destroy the observed correlation between $M_V$ and $\gamma$. Strong cusps form naturally in stellar systems where the black hole grows on time scales long compared with the crossing time (Peebles 1972; Quinlan et al. 1995). Milosavljević & Merritt (2001) presented simulations where the initial galaxies have steep central density cusps (like those in low-luminosity galaxies) and central black holes. The central density cusp in the final remnant had a slope $\rho \sim r^{-1}$ after the binary black hole had ejected a mass of order its own mass from the pre-existing nucleus. This result can explain how shallow cusps form. In this work, we describe a set of merger simulations that address the question of how a shallow cusp can survive the accretion of a small dense galaxy. Our work extends that of Merritt & Cruz (2001; hereafter Paper I) who first presented merger simulations of galaxies containing central black holes and density cusps.
2. Method

Initial galaxies were generated from Dehnen’s (1993) law,
\[
\rho(r) = \frac{(3 - \gamma) M}{4 \pi a^3} \left( \frac{r}{a} \right)^{-\gamma} \left( 1 + \frac{r}{a} \right)^{\gamma - 4},
\]
which has a power-law central density dependence, \( \rho \propto r^{-\gamma} \). Our primary (massive) galaxies had \( \gamma = 1 \), characteristic of the shallow cusps in bright galaxies, and our secondary (dwarf) galaxies had \( \gamma = 2 \), characteristic of the steep cusps of dwarf galaxies. Subscripts 1 and 2 will henceforth refer to the primary and secondary galaxies respectively. Initial particle velocities were assigned from an isotropic distribution function that accounts for the central point mass representing the black hole (Tremaine et al. 1994). Each black hole was assigned a mass \( 2 \times 10^{-3} \) times that of the parent galaxy. This is consistent with the best estimated value of \( \sim 0.0012 \) for the mean ratio of black hole mass to luminous galaxy mass in the local universe (Merritt & Ferrarese 2001).

The mass \( M_1 \) and length scale \( a \) of the primary galaxy were set to unity. We chose \( M_1/M_2 = 3 \); this mass ratio complements the more extreme ratio of \( M_1/M_2 = 10 \) adopted in Paper I. As in that paper, the ratio of the galaxies’ scale lengths was fixed using scaling relations drawn from observations of real galaxies. In particular, for \( \gamma_1 = 1 \) and \( \gamma_2 = 2 \), we took \( r_{e,2}/r_{e,1} = (M_2/M_1)^{3/5} \). The primary galaxy had \( N_1 = 5 \times 10^5 \) equal-mass particles. For the secondary galaxy we took \( N_2 = (M_2/M_1)N_1 = 1.66 \times 10^5 \) so that all particles had the same mass. We set the initial orbital parameters for the mergers such that the separation between the galaxy centers was \( \sim 3 \) times the half-mass radius of the primary galaxy. The initial orbital velocities were assigned in units of the angular momentum of a circular orbit at the defined separation, \( \kappa \equiv L/L_{\text{cir}} \), with \( \kappa = \{0, 0.2, 0.5, 0.8\} \).

The evolution was followed using the tree code GADGET (Springel et al. 2000), a parallel algorithm with continuously-variable time steps for each particle. The merger simulations were continued until \( \sim 1 \) dynamical time of the primary galaxy after formation of the hard black-hole binary, slightly longer than in the simulations of Paper I. Integrations were carried out using the HPC10000 supercomputer at the Rutgers Center for Advanced Information Processing and the Cray T3E at the San Diego Supercomputer Center. All simulations used 16 processors.

3. Results & Discussion

Final density profiles for the merger remnants are shown in Figure 1, computed from the particle positions using the MAPEL package (Merritt 1994). We also plot final density profiles from the 10 : 1 mergers of Paper I; because those simulations were extended for slightly longer times here, the central densities have dropped slightly compared to the values shown in Paper I due to continued ejection of stars by the black-hole binary.

The central density slopes for all of our simulations are lower at the final time step than the initial slope of the giant galaxy. We find \( 0.5 \lesssim \gamma \lesssim 1 \) for
Figure 1. Final density profiles (a-c) and projected density profiles (d-f) for all remnants in our simulations. The four thin curves in each frame correspond to different initial orbits; the thin curve extending farthest to the left corresponds to $\kappa=0.8$ and the shortest to $\kappa=0$. Thick lines are the initial profiles. In (a) and (d) we show mergers of galaxies with central black holes and mass ratio 3 : 1; in (b) and (e) the mass ratio is 10 : 1. In (c) and (f) we show the final density profiles for 10 : 1 mergers in which neither galaxy contained a black hole.
the 3 : 1 mergers and $\gamma \lesssim 1$ for the 10 : 1 mergers. In projection, all of the remnants exhibit “cores,” regions of nearly constant surface brightness near the center; the cores are especially noticeable in the 3 : 1 remnants. This is similar to the situation in real elliptical galaxies, where nonparametric deprojection of the luminosity profiles of the “core” galaxies reveals shallow power-law cusps in the space density (Merritt & Fridman 1995). The very mild inflections seen in the projected density profiles of Figure 1 are also consistent with observed profiles.

Based on these simulations, and on the 1 : 1 merger simulations of Milosavljević & Merritt (2001), we propose the following two rules that relate initial and final density profiles at the centers of merging galaxies. 1. Mergers between galaxies containing power-law density cusps produce remnants with power-law cusps. 2. The final density profile is always shallower near the center than the initial profile of the more massive galaxy. The first “law” appears to be true even in mergers without black holes (Figure 1c,f; Barnes 1999), while the second “law” only holds if the massive galaxy contains a supermassive black hole. Central densities might be driven even lower by the continued ejection of stars by a binary supermassive black hole (Milosavljević & Merritt 2001). These “laws,” if they can be shown to hold generally for mergers between galaxies with supermassive black holes, could explain how the observed relation between $M_V$ and $\gamma$ is preserved in the face of mergers.

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