CUSP DISRUPTION IN MINOR Mergers

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ABSTRACT

We present 0.55 × 10^6 particle simulations of the accretion of high-density dwarf galaxies by low-density giant galaxies, using models that contain both power-law central density cusps and point masses representing supermassive black holes. The cusp of the dwarf galaxy is disrupted during the merger, producing a remnant with a central density that is only slightly higher than that of the giant galaxy initially. Removing the black hole from the giant galaxy 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 is a consequence of supermassive black holes.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: evolution — galaxies: interactions — galaxies: nuclei

1. INTRODUCTION

Bright spheroids (elliptical galaxies and the bulges of spiral galaxies) tend to be less dense than faint spheroids, in two distinct ways. Bright spheroids have larger scale lengths, r_s ∝ L^{1/4}, and lower mean densities within r_e, where r_e is the half-light radius and L is the total luminosity. Bright galaxies also tend to have density profiles that are less concentrated toward the center. The luminosity densities of elliptical galaxies and bulges rise approximately as power laws at the smallest observable radii, ρ_g ∝ r^−γ. Faint galaxies (M_g ≈ −20) have 1.5 ≤ γ ≤ 2.5, while bright galaxies have 0 ≤ γ ≤ 1.5 (Crane et al. 1993; Ferrarese et al. 1994; Gebhardt et al. 1996).

The existence of the second correlation raises two questions. Why do bright galaxies have lower central concentrations than do faint galaxies and how is this correlation maintained in the face of mergers? Big galaxies will sometimes accrete small galaxies, and the small galaxy will be resistant to tidal disruption because of its higher density (Kormendy 1984; Balccells & Quinn 1989). A small galaxy that survived such a merger with its central regions intact would create a new, high-density core in the merger remnant, destroying the observed correlation between L and γ.

The survivability of compact galaxies during mergers is relevant to the origin of galaxies with kinematically distinct cores. Forbes, Franx, & Illingworth (1995) investigated whether the properties of such galaxies were consistent with the accretion hypothesis. They found no strong evidence for abnormal surface brightness profiles (“cores within cores”) but noted that “This problem can possibly be circumvented by adding a massive black hole to the host galaxy. The [host] galaxy might be able to disrupt the victim galaxy, resulting in a density profile more like that which is seen.” They suggested that “Simulations with realistic density profiles and possible black holes would be valuable.”

Here we present the results of such simulations. We consider mergers between initially spherical galaxies with a mass ratio of 10 : 1; each galaxy has a power-law central density cusp as well as a central point mass representing a supermassive black hole. The galaxies’ structural parameters are scaled in accordance with observed relations (§2). We find, in agreement with the suggestion of Forbes et al. (1995), that the black hole in the primary galaxy is effective at disrupting the cusp of the secondary galaxy, yielding a remnant density profile that is only slightly more centrally concentrated than that of the primary galaxy at the start of the simulation.

2. METHOD

The initial galaxies were generated from Dehnen’s (1993) spherical density law, ρ(r) = [(3 − γ)M/4πa^3](r/a)^−γ(1 + r/a)^−1. Initial particle velocities were assigned from the unique isotropic distribution function that reproduces Dehnen’s density law in the combined potential of the stars and a central point mass representing the black hole (Tremaine et al. 1994). Our primary galaxy had γ = 1, characteristic of the shallow cusps of bright galaxies, and our secondary galaxy had γ = 2, characteristic of the steep cusps of dwarf galaxies. Each “black hole” was assigned a mass of 2 × 10^5 times that of its parent galaxy. This is slightly above, but consistent with, the current best estimate of ~0.0012 for the average ratio of black hole mass to luminous galaxy mass in the local universe (Merritt & Ferrarese 2001). Henceforth, the subscripts 1 and 2 will refer to the primary (massive) and secondary (dwarf) galaxies, respectively. All of the simulations had M_1/M_2 = 10.

The mass M_i and scale length a_i of the primary galaxy were set to unity. The orbital period at the half-mass radius of the primary is ~33.3 in model units. The scale length of the secondary galaxy was computed from the relation

\[ \frac{a_2}{a_1} = \frac{r_{eff,2}}{r_{eff,1}} \left( \frac{r_{eff,1}}{a_1} \right)^{1/2}, \]

where the ratio r_{eff}/a between effective radius and scale length is given by Dehnen (1993) as a function of γ. Real spheroids have r_e ∝ L^γ and MIL ∝ L^β, with MIL being the mass-to-light ratio of the stars; hence, r_e ∝ M_1/M_2(a_1/a_2)^{1/2}. Setting α ≈ 0.75 (e.g., Valluri & Merritt 1998) and β ≈ 0.25 (e.g., Faber et al. 1987) gives r_e/α ≈ (M_1/M_2)^{1/5}. Using our assumed mass ratio of 10 : 1 and the adopted values for γ, equation (1) then implies a_2/a_1 = 0.618.

The center of the secondary galaxy was initially displaced from the center of the primary galaxy by ~3 times the half-
accuracy parameter was chosen so as to require a further set of runs was carried out in which neither galaxy point mass. To test the importance of the primary’s black hole, galaxy with the same initial density profile but lacking a central on the evolution, each run was repeated using a secondary HPC-10000) and at the San Diego Supercomputer Center (Cray Rutgers Center for Advanced Information Processing (a Sun integrations are the softening length \( h \) and the time step parameter \( \eta \). We chose \( h = 8 \times 10^{-4} \), slightly smaller than the radius \( \sim 10^{-3} \) at which the two black holes would be expected to form a hard binary. This softening length corresponds to \( \pm 1 \) pc with typical scalings. Our value \( \eta = 0.008 \) for the accuracy parameter was chosen so as to require \( \gtrsim 10^5 \) time steps for a star in a circular orbit with radius \( h \) around the large black hole. Extensive testing was carried out to ensure that the selected values for the tree-code parameters resulted in no changes in the density profiles of either galaxy on length scales \( \gtrsim 10^{-3} \) when integrated in isolation. The merger simulations were continued until roughly 1 crossing time of the primary galaxy after formation of the hard black hole binary. Integrations were carried out on the parallel supercomputers at the Rutgers Center for Advanced Information Processing (a Sun HPC-10000) and at the San Diego Supercomputer Center (Cray T3E). All simulations used 16 processors.

In order to test the influence of the secondary’s black hole on the evolution, each run was repeated using a secondary galaxy with the same initial density profile but lacking a central point mass. To test the importance of the primary’s black hole, a further set of runs was carried out in which neither galaxy contained a black hole. The velocity distribution functions for the models without black holes were computed as in Dehnen (1993).

3. RESULTS

The results are summarized in Figures 1 and 2. Figure 1a shows, for \( \kappa = 0.2 \), the number of particles initially associated with the two galaxies that remain within spheres of radius 0.1 (primary) and 0.05 (secondary) around their respective black holes; these are roughly the respective radii inside of which the final density profile of each galaxy shows substantial evolution. Figure 1 reveals two ways in which the merger causes the central density of the final object to be less than the sum of the central densities of the two initial objects. (1) The density of stars around the black hole in the primary galaxy drops steadily throughout the simulation and drops suddenly whenever the secondary galaxy passes near the primary’s center; the drops are preceded by jumps resulting from the impulsive increase in the gravitational force caused by the passage of the small galaxy. (2) The density of stars around the black hole in the secondary galaxy also drops, but only after the secondary passes sufficiently close to the center of the primary. In the case of plunging orbits, \( \kappa = 0 \) or 0.2, the first close passage occurs during the first infall; the drop in density of the secondary is again preceded by a jump indicating that the mechanism is an impulsive addition of energy, this time from the gravitational force of the primary’s black hole. In the case of the more circular orbits, \( \kappa = 0.5 \) and 0.8, the central density of the secondary remains high until the radius of its orbit has decayed to \( \sim 0.1 \).

The presence of the black hole in the secondary galaxy might naively be expected to contribute to the stability of that galaxy’s core by enhancing the gravitational force there. In fact, the opposite is true: the density at late times in the runs without a second black hole is generally higher than in the run with two black holes (Fig. 1a). This is probably a consequence of the three-body ejection of stars by the pair of black holes (Quillan 1996). However, the softening of the interparticle forces in GADGET does not permit this process to be followed with high accuracy. The final central densities that we observe in the runs with two black holes should therefore be interpreted as upper limits. Removing the black hole from the primary galaxy has almost no effect on its evolution, but the central density of the secondary galaxy now remains high throughout the merger (Fig. 1b).

Figures 2a–2d show the final density profiles from the four runs in which both galaxies contained black holes. The profiles are centered on the black hole binary and were computed using MAPEL.\(^3\) The secondary’s density (Fig. 2a) is lowered at small radii, \( r \lesssim 0.05 \), because of the impulsive heating from the primary black hole and at large radii, \( r \gtrsim 0.1 \), because of the tidal forces from the primary galaxy. The greatest decrease in central density occurs in the runs with lowest \( \kappa \), i.e., the most plunging orbits. In the case of stars initially associated with the primary galaxy, the final density profile is remarkably independent of \( \kappa \) (Fig. 2b). The primary galaxy was found to exhibit always a \( \rho \sim r^{-0.5} \) central density cusp at the end of the simulations; a similar result was found by Nakano & Makino (1999a, 1999b) when they dropped a black hole into the core of a galaxy containing no black hole. The net result (Fig. 2c) is a remnant density

\(^3\) See http://www.physics.rutgers.edu/~merritt/mapel_1.html.
profile that rises modestly above that of the initial, primary galaxy at small radii, more so in the runs with larger \( \kappa \). However, the slope of the surface brightness profile (Fig. 2d) is only slightly increased near the center compared with that of the primary galaxy. We note that many bright elliptical galaxies also show mild inflections in their central surface brightness profiles on similar scales (e.g., Fig. 1 of Merritt & Fridman 1995), perhaps relics of past mergers.

When the black hole is removed from the primary galaxy, the secondary galaxy survives the merger intact, with almost no change in its density profile at small radii (Fig. 2e). The final density profile of the remnant is roughly a superposition of the two initial profiles (Fig. 2g); a substantial inflection in the surface brightness profile now appears at a radius of \( \sim 0.1 \) (Fig. 2h). Profiles of this sort are rarely if ever observed in the brightest elliptical galaxies (Ferrarese et al. 1994; Gebhardt et al. 1996).

4. DISCUSSION

Our merger simulations are the first in which the central densities of the merging galaxies are realistically high and in which both galaxies contain “black holes.” Barnes (1999) described mergers of identical Dehnen models with cusp slopes \( \gamma = \{1, 1.5, 2\} \) but without black holes; he found that the cusps survived the mergers with little change. We find a similar result here in the runs without black holes, except that the density of the primary galaxy falls because of the energy input from the secondary. The opposite case—mergers between galaxies with central black holes but no cusps—has been treated extensively (e.g., Ebisuzaki, Makino, & Okumura 1991; Governato, Colpi, & Maraschi 1994; Makino 1997). A number of authors have investigated the effects of dropping one or two black holes into a preexisting galaxy, either with a central density cusp (Quinlan & Hernquist 1997) or without (Nakano & Makino 1999a, 1999b). The simulations closest in spirit to ours are those of Holley-Bockelmann & Richstone (2000). These authors followed the evolution of a dense secondary galaxy as it moved in the fixed gravitational field of a less-dense primary containing a black hole; the secondary contained no black hole. The decay of the secondary’s orbit was induced artificially using standard expressions for the dynamical friction, with corrections due to the changing mass of the secondary. Since the density of the primary...
galaxy was fixed in these simulations, the authors did not observe the drop in the primary’s central density that we see here (Fig. 2b); hence, the central densities of their merger remnants were too high, partly explaining their conclusion that all but the most plunging orbits resulted in merger remnants with unphysically steep cusps. Holley-Bockelmann & Richstone also observed a stronger dependence of the secondary’s density evolution on its initial orbit than is seen here, probably because of the approximate way in which orbital decay was treated.

Our results support the hypothesis that the persistence of low-density cores in giant galaxies is a consequence of the existence of supermassive black holes (Forbes et al. 1995). The central density did nevertheless increase in our simulations, and since a typical bright galaxy is expected to have accreted many smaller galaxies since its formation (e.g., Lacey & Cole 1993), one might still predict the formation of dense nuclei in bright galaxies, contrary to what is observed. However, our simulations are not able to follow the evolution of a black hole binary on subparsec scales as it ejects stars from the core and lowers the density there still more (Quinlan 1996). Future work should be directed toward understanding the effects of hierarchical mergers on galaxy density profiles, using $N$-body codes that can deal efficiently with unsoftened particles and hence follow the interaction of a binary black hole with the surrounding stars.

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