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Gravitational Cold Collapse with Supermassive Black Holes

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Abstract

We explore a scenario for the formation of cuspy profiles where a preexisting central supermassive black hole is present during a galactic cold collapse. The simulations were evolved using a collisional *N*-Body code. Our results suggest that a central cuspy density profile can be produced in this scenario. The final slopes of our cuspy profiles correspond to the observed values of early-type galaxies.

1.1 Introduction

From ground-based/HST observations and theoretical arguments, it is now widely accepted that supermassive black holes (SBHs) are present in galactic nuclei (Ferrarese & Merritt 2000, Kormendy & Richstone 1995). These objects contain a large fraction of the central mass ($10^7 - 10^9$ $M_\odot$) and they should have a substantial influence on the dynamics and evolution of their surrounding stars and gas. Peebles (1972) and Young (1980) noted that the growth of a black hole in a preexisting stellar core would give rise to the formation of a power-law central density cusp. It has been found that a considerable fraction of early-type galaxies exhibit cuspy density profiles (Gebhardt et al. 1996). Dynamical modeling of an adiabatically growing black hole inside isothermal cores provides a good representation of the observational data (van der Marel 1998), however, this implies that the black hole increases its mass through the accretion of external gas rather than by disrupting stars (Stiavelli 1998). Previous simulations by Merritt and Quinlan (1998) showed that a cuspy profile forms if the mass of the central black hole grows adiabatically inside an isothermal core. Furthermore, observations indicate a tight correlation between the mass of SBHs and the velocity dispersion of its surroundings, suggesting that the formation and evolution of galaxies with the central black hole are intimately correlated.

The question that arises is the following: Is the adiabatic growth of a black hole the only feasible scenario that may explain the formation of a central cuspy density profile and the central kinematics of galactic nuclei? The aim of this work is to consider a complementary scenario where, the formation of cuspy density profiles would occur during the formation of a galaxy through cold gravitational collapse around a preexisting central supermassive black hole.

Table 1.1. *Initial parameters for our models*

Model	M_{bh}/M_g	n	$\beta(2\sigma_r/\sigma_\perp)$	η $(2K/W)$	N $(\times 10^3)$
A0	0.0	1	1	0.05	32
A1	0.01	1	1	0.05	32
B0	0.0	3/2	1	0.05	32
B1	0.01	3/2	1	0.05	32

1.2 Method

We set up a series of N-body simulations to study the effect of a central black hole. Initially, the positions for the particles are randomly drawn from a power-law density profile given by (Hozumi, Burkert & Fujiwara 2000):

$$\rho(r) = \frac{M}{2\pi R_0^3}(\frac{r}{R_0})^{-n} \tag{1.1}$$

where M is the total mass and R_0 is the initial radius of the sphere. In our experiments a power-law index of $n = 1, 3/2$ is assumed.

The velocities are obtained from the following distribution:

$$f = \frac{\rho(r)}{\sqrt{2\pi^{3/2}\sigma_r\sigma_\perp^2}} \exp\left(-\frac{u^2}{2\sigma_r^2}\right) \exp\left(-\frac{j^2/r^2}{\sigma_\perp^2}\right), \tag{1.2}$$

where σ_r and $\sigma_\perp$ are the radial and tangential velocity dispersions, respectively, and j the angular momentum. In these models the anisotropy parameter is defined as $\beta \equiv 2T_r/T \perp$ or, equivalently, as $2\sigma_r/\sigma_\perp$, where T_r and $T_\perp$ are the kinetic energies in radial and tangential motions. We have chosen a system of units such that $M = G = 1$ and a total energy of $E = -1/4$. In these units the free-fall time-scale is $t_{ff} \approx 5$. All our models are initially isotropic, and the virial ratio is 0.05 (see Table 1).

The mass of the SBH was taken to be 0.01 of the total mass of the galaxy. Although this mass is bigger than the observed values, it is still consistent with the masses reported for the more massive black holes. Initially the black hole is is placed in rest at the center of the system. The parameters that characterize our numerical simulations are summarized in Table 1. We evolve the models A for about 40 crossing time units at the half mass radius ($\approx 8t_{ff}$). We follow the models B by 16 crossing times at the half mass radius ($\approx 4t_{ff}$). At these times, the resulting central regions have completely relaxed allowing to compute their central density profiles. The energy conservation was better than 0.0001% in all cases.

The evolution of these gravitational collapses was followed with a Systolic algorithm, a collisional code developed for parallel computers (Dorban et al. 2003) that uses the Hermite integrator with variable time steps for the particles. These numerical simulations were performed in a Beowulf cluster located at the Instituto de Astronomía, UNAM-Ensenada.

Finally, the density profiles were computed from the particle positions using the MAPEL package (Merritt 1994).

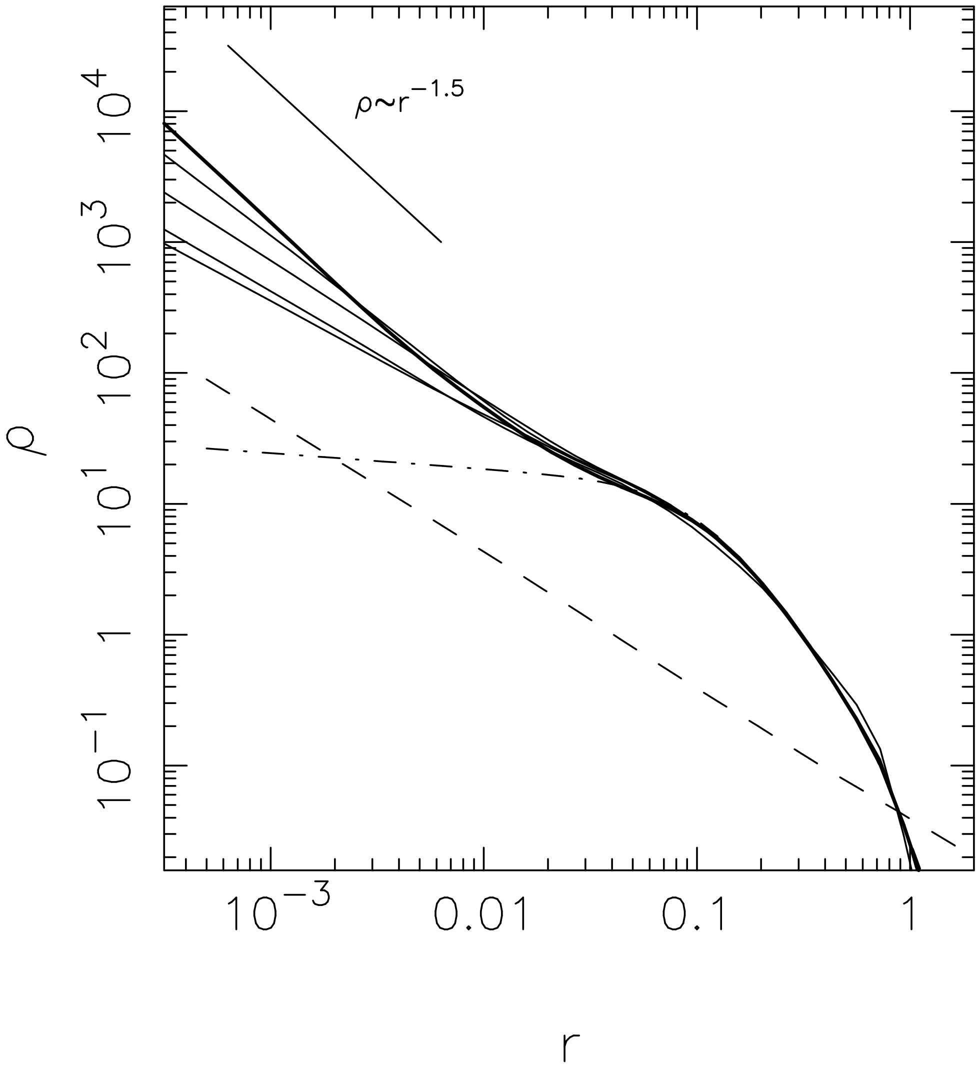

Fig. 1.1. Density profiles for our models A (see Table 1). Dashed line is the initial density profile. Dashed-dotted line corresponds to the final configuration of the model A0 without central black. The thin-solid lines indicate the time evolution of the density profile. The solid thick line shows the final density profile for model A1. For comparison we have included a reference line with a logarithmic slope of -1.5

1.3 Results

Figure 1.1 shows the final density profiles for our gravitational cold collapse models A0 and A1 listed in Table 1. It is evident that a preexisting black hole strongly modifies the inner region of model A1 given place to the formation of a central cusp. The central region in this model is about 2.5 orders of magnitude (thick line) bigger than in our model A0 (dahsed-dotted line) without a central massive black hole. The evolutive trend of the density profile of model A1 is also illustrated in this figure, the thin lines correspond to the density

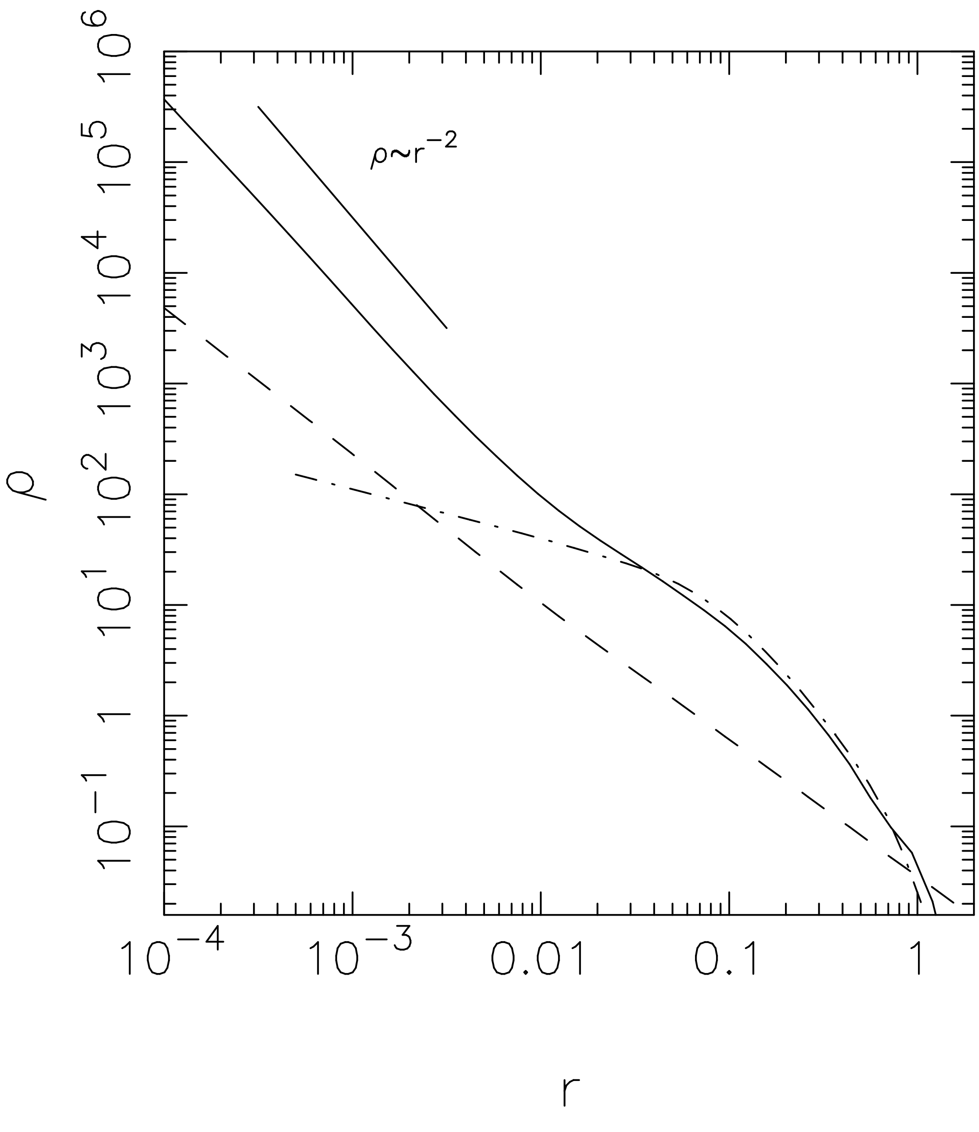

Fig. 1.2. Density profiles for our models B (see Table 1). The initial density profile is indicated by the dashed line. The final profile for our model B0 without a central black hole corresponds to the dashed-dotted line. The thick solid line shows the final density profile for our model B1 with a SBH. In this case the reference line has a logarithmic slope of -2.0

at times $t = 10, 20, 30, 40$ from bottom to top. At the end of the simulation, model A1 shows a central density profile with logarithmic slope of -1.5.

The final density profiles for our models B0 and B1 listed in table 1 are plotted in Figure 1.2. These models are evolved for about 4 times the free-fall timescale, or 16 crossing times at the half mass radius. The final central density for our model B1 (thick line) is about 3.5 orders of magnitud bigger than in model B0 (dashed line. For this case the central density profile has a logarithmic slope of -2. These last models poses a great challenge for the N-body code given the small number of particles near to the central SBH and to the short dynamical time scales involved in this region. The difficult of this simulation is the small number of particles and the dynamical scales involved in this simulation.

1.4 Discussion and Conclusions

We have showed than central cuspy profiles may form through gravitational cold collapse around a preexisting black hole (see Figures 1.1 and 1.2). Models without a central SBH tend to form a core rather than a cusp. The cuspy density profile of our model B1 resembles the one obtained by Merritt & Quinlan (1998, see their Figure 3a). These authors produce this cuspy profile by an adiabatic growth of a central black hole in an isothermal core. Our preliminar analysis are qualitatively similar to those results. So far, we can not distinguish between both scenarios with this analysys.

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