HALO DENSITY REDUCTION BY BARYONIC SETTLING?

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ABSTRACT

We test the proposal by El-Zant et al. that the dark matter density of halos could be reduced through dynamical friction acting on heavy baryonic clumps in the early stages of galaxy formation. Using N-body simulations, we confirm that the inner halo density cusp is flattened to 0.2 of the halo break radius by the settling of a single clump of mass \( \gtrsim 0.5 \% \) of the halo mass. We also find that an ensemble of 50 clumps, each having masses \( \gtrsim 0.2 \% \), can flatten the cusp to almost the halo break radius on a timescale of \( \sim 9 \) Gyr, for a Navarro–Frenk–White profile halo of concentration 15. We summarize some of the difficulties that need to be overcome if this mechanism is to resolve the apparent conflict between the observed inner densities of galaxy halos and the predictions of \( \Lambda \) CDM.

Key words: galaxies; evolution – galaxies: formation – galaxies: halos – galaxies: kinematics and dynamics

Online-only material: color figures

1. INTRODUCTION

The \( \Lambda \) CDM model for structure formation in the universe has been very successful on large scales (e.g., Springel et al. 2006), but has run into a number of difficulties on galaxy scales. One difficulty is that the predicted dark matter (DM) density in the halos of bright galaxies appears to be greater than that inferred from the best observational data (e.g., Weiner et al. 2001; Dutton et al. 2007) or from dynamical friction constraints (Debattista & Sellwood 2000); see Sellwood (2009) for a review.

A number of possible solutions have been suggested. Binney et al. (2001) and others suggested that the halo density can be reduced by feedback from star formation, but Gnedin & Zhao (2002) showed that the density cannot be reduced by more than a factor of 2, even for the most extreme feedback, unless the baryons are unreasonably concentrated. Weinberg & Katz (2002) proposed that dynamical friction between a bar and the halo can reduce the central density, but Sellwood (2008) showed that significant reductions require extreme bars and remove a large fraction of the angular momentum from the baryons.

A third possible solution was proposed by El-Zant et al. (2001, hereafter EZ01), who suggested that dynamical friction between heavy gas clumps and dark matter would transfer energy to the dark matter, thereby reducing its inner density.

Essentially, EZ01 proposed a process of mass segregation that allows the baryonic matter to displace the dark matter. If it works, it would amount to baryon settling with halo decompression, as Dutton et al. (2007) argued would be required to improve agreement of \( \Lambda \) CDM predictions with scaling relations of \( \sim L_\star \) galaxies. Kassin et al. (2006) also remarked that rotation curves could be more easily reconciled with \( \Lambda \) CDM predictions if halo compression could somehow be avoided. Tonini et al. (2006) used the idea to predict rotation curves for galaxies. Mo & Mao (2004) applied the mechanism to preprocess small halos in the very early stages of structure formation.

A similar, but significantly distinct, idea was tested by Gao et al. (2004), who argued that some unspecified attractor mechanism causes violent relaxation processes to reset the collisionless mass profile of the combined dark and baryonic matter. Since violent mergers disrupt disks, Gao et al. clearly invoked a different process from the slow frictional in-spiral of baryonic clumps proposed by EZ01.

EZ01 supposed that the baryons collect into dense mass clumps, which then sink to the center by dynamical friction. They assumed that (1) the clumps are small enough that they do not collide and (2) are sufficiently tightly bound that they are not tidally disrupted. They also implicitly assumed that the dense clumps (3) maintain their coherence independent of any internal physical processes (such as possible star formation) and (4) they required the mass clumps to contain little dark matter.

The in-spiral of massive clumps has been studied extensively and we do not attempt a complete list of references. Van den Bosch et al. (1999) estimated the infall rate of dark matter subclumps through dynamical friction. Ma & Boylan-Kolchin (2004) simulated a mass spectrum of satellites, each composed of particles moving within a main halo; they found that the combined density profile of the inner halo and disrupted satellites can either steepen or flatten, depending on the properties of the clumps. Arena & Bertin (2007) studied both the strength of the friction force and the effect on the density profile for both cuspy and cored initial galaxy profiles.

Here we undertake a direct test of the proposal by EZ01, using self-consistent N-body simulations, in order to determine the clump mass required to effect a significant density reduction. We first derive the settling timescale for single massive clumps that settle to the cluster center. Both EZ04 and Nipoti et al. (2004) presented simulations to show that the in-spiral of galaxies can cause the background dark matter density profile to flatten, although both studies neglect the (DM) halos attached to the infalling galaxies. In the Appendix, we show that our simulations are in good agreement with those of EZ04 for the same problem.
2. MODEL AND METHOD

In this work, we adopt the Navarro–Frenk–White (NFW) halo density profile (Navarro et al. 1997):

\[ \rho(r) = \frac{\rho_s r_s^3}{r(r+r_s)^2}, \]

where \( r \) and \( \rho_s \), respectively, set the radius and density scales. Since the mass is logarithmically divergent at large radii, we adopt \( M_s = 4\pi \rho_s r_s^3 \) as a convenient mass scale; for reference, \( M_s \) is the mass enclosed within \( r \approx 5.305r_s \) and the mass enclosed within a sphere of \( 15r_s \) is \( \approx 1.835M_s \). An isotropic distribution function (DF) for the NFW halo can be obtained by Eddington inversion (Binney & Tremaine 2008, Equation (4.46)). We limit the radial extent of the halo by eliminating all particles with energy \( \epsilon \) below a certain value (Equation (4.46)). We limit the radial extent of the halo by eliminating all particles with energy \( \epsilon < \frac{1}{2} \).

In this work, we generally adopt a finite softening kernel, \( \epsilon = 0.15r_s \) in an NFW halo, with an initially circular orbit starting at \( r = 4r_s \). We represent the halo with \( 10^6 \) particles, use a grid with 300 radial shells, expand up to \( t_{\text{max}} = 4 \) and employ a basic time step of \( 0.005(r_s^3/M)^{1/2} \). While the decay rate of the satellite orbit is independent of most numerical parameters, it is marginally increased, by \( \approx 1\% \), when we increase \( t_{\text{max}} \) to 10, and it also weakly depends on the softening length adopted for the satellite, as discussed below.

3. A SINGLE SATELLITE

We begin by revisiting the orbital decay of a single massive satellite. The problem of dynamical friction on a heavy particle orbiting in a spherical system of light particles has been worked on extensively. Our purpose here is simply to determine the settling time of a softened heavy particle in a cuspy halo, before going on to study the behavior of a collection of such particles in Section 4.

Our fiducial run uses a satellite of mass \( M_h = 0.01M_\odot \) with \( \epsilon = 0.15r_s \) in an NFW halo, with an initially circular orbit starting at \( r = 4r_s \). We represent the halo with \( 10^6 \) particles, use a grid with 300 radial shells, expand up to \( t_{\text{max}} = 4 \), and employ a basic time step of \( 0.005(r_s^3/M)^{1/2} \). While the decay rate of the satellite orbit is independent of most numerical parameters, it is marginally increased, by \( \approx 1\% \), when we increase \( t_{\text{max}} \) to 10, and it also weakly depends on the softening length adopted for the satellite, as discussed below.

3.1. Settling Time

Figure 1 (upper) shows the time evolution of the angular momentum of the satellite. The rate of loss due to dynamical friction accelerates as the satellite settles to the center, whereupon further change abruptly ceases. Thus, it takes \( \approx 260 \) dynamical times, or \( 7.8 \) Gyr, for the satellite to settle to the center of the NFW halo from its initial radius. The settling time will be longer in lower density halos or if the satellite starts farther out.

The well known formula (Chandrasekhar 1943; Binney & Tremaine 2008) for the acceleration \( a_f \) of a heavy particle moving at velocity \( v \) through a sea of light particles of constant density \( \rho \) is

\[ a_f(v) = -\frac{v^2}{2\pi} \ln\Lambda G^2 \frac{M_h}{\sigma^2} V \left( \frac{v}{\sigma} \right). \]

Here \( v = |v| \), \( \ln\Lambda \) is the usual Coulomb logarithm, and

\[ V(x) = x^{-2} \left[ \text{erf} \left( \frac{x}{\sqrt{2}} \right) - \left( \frac{2}{\pi} \right)^{1/2} xe^{-x^2/2} \right]. \]
the quantity in the square brackets is the fraction of light particles having speed \(< v\), assuming the particles to have a Maxwellian velocity distribution with dispersion \(\sigma\). While the assumptions made in the derivation of this formula do not strictly permit it to be applied to the present problem (e.g., Tremaine & Weinberg 1984), it correctly predicts the scaling with parameters (e.g., Lin & Tremaine 1983; Sellwood 2006; Arena & Bertin 2007).

The lower panel of Figure 1 compares the prediction of formula (5) with our numerical results. The solid curve shows the rate of loss of angular momentum by the satellite, while the dashed curve shows the expected torque, \(r' \times a_f\), using local values for the density and velocity dispersion of the halo particles.\(^1\) We treat the Coulomb logarithm, which is not predicted with any certainty, as a free scaling parameter; the curve shown is for \(\ln \Lambda = 2.5\). The agreement is satisfactory until the final plunge of the satellite, where the empirical torque drops below that predicted. We have verified that the frictional torque scales appropriately with the local density and velocity dispersion, and linearly with the mass of the heavy particle for \(M_h \lesssim 0.05 M_*\).

The low value of \(\ln \Lambda\) required to match our data is not purely a consequence of satellite softening. The solid line in Figure 2 shows that the time taken for a satellite of mass \(M_h = 0.01\) to settle to the center from a circular orbit at \(r = 4\) varies approximately linearly with the softening length. As is reasonable, more concentrated satellites settle more rapidly, but the variation is by a factor of \(\sim 1.5\) for a factor of 10 change in the softening length, which is a somewhat slower dependence than \(\ln \epsilon\). Low values of \(\ln \Lambda\) are widely reported in other work (e.g., Boylan-Kolchin et al. 2008 and references therein), and are discussed in the Appendix of Milosavljević & Merritt (2001).

Figure 2 also compares the results using the cubic softening kernel (solid line) with those from the more traditional Plummer rule (dashed line). The results compare well when the Plummer softening length is about \(1/3\) of that for the sharper cubic kernel. For both softening rules, we find that the torque is reasonably well predicted by Equation (5) for the same \(\ln \Lambda\) when \(\epsilon\) is scaled by this factor.

We have run a small number of additional experiments with satellites on initially noncircular orbits. The Chandrasekhar friction formula (Equation (5)) continues to predict the rate of angular momentum loss, with the same \(\ln \Lambda\). Generally, the settling time when the orbit is not strongly eccentric is only slightly longer than that from a circular orbit with the same initial angular momentum. More eccentric orbits take longer to settle, because the satellite spends more time at radii well beyond its guiding center radius where the background density is lower. It should be noted that adding radial motion at fixed angular momentum, as we discuss here, increases the satellite’s energy, so our conclusion remains consistent with other work (e.g., van den Bosch et al. 1999).

Our experiments have been confined to spherical dark matter halos, whereas halos are expected to be mildly triaxial (e.g., Jing & Suto 2002). A mass clump in a triaxial halo may pursue a box orbit (Binney & Tremaine 2008, chapter 3), causing it to...
pass through the dense center from time to time and possibly reducing the settling time (e.g., Pesce et al. 1992). However, such orbits are already eccentric and settle more slowly than quasi-circular orbits.

3.2. Halo Density Changes

As the satellite settles to the center, the halo particles are heated and the density of the inner halo decreases. Figure 3, from our fiducial run, shows the time evolution of the radii containing many different mass fractions, indicating that the mass profile undergoes little change until after time 250. These Lagrangian radii are always computed from a center at the densest point. Since the distance of the satellite from the center falls below $r_s$ only after $t \sim 250$, most of the change to the mass profile of the halo occurs during the final plunge of the satellite through the cusp, in agreement with the conclusions of EZ01.

Figure 4 shows the density and mass profiles after the satellite has settled from the same initial orbit in each case. The changes are not large: the cusp is flattened inside $r \lesssim 0.2r_s$ in our fiducial run (upper panel), where the satellite mass is $0.01M_\ast$ or $\gtrsim 0.5\%$ of the halo mass. The changes produced by heavier and lighter infalling masses differ in the expected sense. These measurements of the density and mass profiles are, at all times, from a center located at the densest point.

4. COLLECTION OF HEAVIES

Dark matter and baryons are well mixed in the early universe. As halos form, the relative distributions of the collisionless dark matter and the collisional baryonic component become more difficult to predict as shock heating, feedback from star formation, and cold infłows may all occur (e.g., Cattaneo et al. 2007). The typical expectation is that some $5\%$–$15\%$ of a total galaxy’s mass is baryonic.

In their models, EZ01 parameterized the clump mass as $M_{200}/\eta$, where $M_{200}$ is the total (baryonic plus dark) mass of the galaxy. If the baryon fraction is $f$ and all the baryons are in equal mass clumps, the number of clumps is, therefore, $f/\eta$. These authors used the Chandrasekhar dynamical friction formula to predict the rate at which energy is removed from the heavy clumps, which they added to the local dark matter and adjusted its mass profile in response to the energy added at each radius.

Here instead we use $N$-body simulations with both heavy and light particles. Consistent with their assumptions, we treat the baryonic mass clumps as heavy softened particles and integrate their motion through the smooth background halo composed of light, collisionless particles.

We first simulate their Model 1, which has a baryonic mass of $10\%$ of the total enclosed within $15r_s$. In this model, the baryons are uniformly distributed inside a sphere of radius $r = 4r_s$, while the dark matter has an NFW distribution. We therefore redetermine the initial equilibrium DF for the halo, in order to take account of the additional central attraction caused by the baryonic matter. In our simulation, the dark matter is represented by 500,000 particles drawn from the new DF, while we set the isotropic initial velocities of the 500 equal-mass heavy particles using the procedure described by Hernquist (1993).

We find some density reduction of the inner NFW profile as the heavy particles settle. Figure 5 shows the density and mass profile of the light (dark matter) particles after 300 dynamical times, or $\sim 9$ Gyr. A small reduction of the dark matter density is achieved over this time when 500 heavy particles represent the entire baryonic mass ($f = 0.1$). Naturally, the effect is increased as the baryonic mass is concentrated into fewer, more massive particles, since each heavy particle experiences stronger friction and settles more quickly.

If the baryonic mass clumps are distributed as the dark matter, mass segregation is even slower. EZ01 found little evolution with $N_h = 500$ in an NFW halo with the heavies distributed as the NFW density profile, which we confirm in a simulation with

![Figure 3](image-url)  
**Figure 3.** The time evolution of the Lagrangian radii in the fiducial run. Each curve shows the radius enclosing a fixed fraction of the halo mass, with the lowest curve corresponding to $2 \times 10^{-4}$, rising by a factor of 2 at each subsequent trace. The changes are minor until the satellite enters the cusp.

![Figure 4](image-url)  
**Figure 4.** The changes in (a) density and (b) mass profile caused by the settling of a single satellite of $0.5\%$, $1\%$, and $5\%$ of the halo mass from an initially circular orbit at $r = 4r_s$ in an NFW halo. The solid lines show the density or mass profiles measured from the particles at the start (black) and when the satellite has settled (color). The dashed lines show the corresponding theoretical NFW curves.

(A color version of this figure is available in the online journal.)
that larger reductions result from more massive particles that also settle more rapidly.

We specifically test the model proposed by EZ01, who divided all the baryons into a number of equal mass clumps that were already somewhat concentrated toward the halo center. We find (Figure 5) that the $\sim 10\%$ baryonic mass fraction must be entirely made up of $\lesssim 150$ equal clumps if the cusp in the dark matter is to be flattened to $r \lesssim r_s$ within 300 dynamical times, which scales to $\sim 9$ Gyr for a $c = 15$ halo.

The principal reason that we observe a more mild density reduction than predicted by EZ01 is that friction is significantly weaker than they assumed. EZ01 and Tonini et al. (2006) adopted $\ln \Lambda \simeq \ln \eta \simeq 8.5$, whereas we find $\ln \Lambda \simeq 2.5$ (Section 3.1), which causes the mass clumps to settle 2–3 times more slowly than they assumed, with a corresponding reduction in the rate energy being given up to the halo.

More massive clumps both spiral in more rapidly and displace more dark matter (Figure 4). Ma & Boylan-Kolchin (2004) presented a pair of simulations that revealed a much smaller density change when the three most massive clumps were eliminated compared with the result when they were retained. Thus, substantial reductions of the inner halo density require just a few extremely massive clumps, assuming that they are not disrupted as they settle.

The timescale, in years, varies as $\rho_c^{-1/2}$, and therefore would be longer in lower concentration halos. At higher redshifts, the orbital period is a fixed fraction of the age of the universe at a constant overdensity (since both scale as the square root of the density in an Einstein–de Sitter universe). While halo densities rise with redshift, their relative overdensities are lower (e.g., Zhao et al. 2003), and, therefore, more massive clumps are required to have any effect in the time available; Mo & Mao (2004) invoked baryon clumps having 5% of the halo mass when $2 \lesssim z \lesssim 5$.

EZ04 argued that the same physical process applies to galaxies in clusters and presented supporting simulations. Again, adopting their numerical model and assumptions, we confirm (Appendix) their result that the density cusp flattens for $r \lesssim 0.2r_s$, where we also demonstrate that the result is independent of the numerical method.

The physical assumptions underlying these successes are more questionable, however. Purely baryonic gas clumps are indeed expected to form through the Jeans instability as gas cools and settles in the main halo (e.g., Maller & Bullock 2004), but the high-resolution experiments of Kaufmann et al. (2006) show that gas fragments formed in this way have masses ranging up to $\sim 10^6 M_\odot$ only, some two orders of magnitude smaller than required to have interestingly short settling times.

Dark matter subhalos (e.g., Diemand et al. 2007) may contain gas and would spiral in more rapidly. However, settling of such subhalos would bring both baryons and DM into the center, diluting the desired separation of baryons from dark matter. The resulting changes to the overall dark matter density profile will clearly be less substantial. When Ma & Boylan-Kolchin (2004) treated subclumps as collections of particles, they found that the stripped mass is added to the main DM halo in such a way as approximately to replace the mass scattered to larger radii by dynamical friction. (The net effect can be either a small increase or decrease in the inner dark matter density, depending on the mass clump spectrum.) If dynamical friction is to separate the baryons from dark matter with the desired efficiency, baryonic mass clumps in subhalos must somehow be stripped of their dark...
matter with high efficiency, without dissolving the gas clumps themselves.

In the case of the cluster simulation, EZ04 described the heavy particles as purely baryonic galaxies. Here again, the change in the central dark matter density will not be as substantial when the dark halos of the galaxies are taken into account, as also noted by Nipoti et al. (2004).

Additional density reduction would be possible if massive baryonic clumps in the center of the halo could be reaccelerated. Models of this kind have been proposed by Mashchenko et al. (2006, 2007), who invoked star-formation activity, and by Peirani et al. (2008), who used active galactic nucleus jets. It should be noted, however, that massive clumps of dense gas are not easily accelerated by these astrophysical processes (e.g., MacLow & Ferrara 1999). The rapid density reduction reported by Mashchenko et al. (2006) occurs because they employed a gas clump of $10^5 M_\odot$ within the cusp driven sinusoidally with a bulk speed that peaked at 18 km s$^{-1}$.

Most halo density reduction occurs as clumps plunge rapidly within the cusp (Figure 3), as noted by EZ01. Therefore, clumps that start out in the cusp fall in more rapidly and are most efficient at displacing the dark matter. However, only a small fraction ($\lesssim 5\%$) of the baryons start out in the cusp, if they are distributed as the dark matter. The desired halo density reduction would be more rapid if the baryonic fraction in the cusp could be increased, but it is hard to see how such an initial mass segregation could have arisen without compressing the halo.

Thus, the challenge, if the proposal by EZ01 is to help solve the central density problem of dark matter halos, is to find ways to collect gas into clumps exceeding $\sim 0.5\%$ of the halo mass that can settle as coherent entities into the center.

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APPENDIX

GALAXY CLUSTER SIMULATIONS

El-Zant et al. (2004) presented results from simulations using a nonadaptive Cartesian grid covering only the inner part of the dark matter halo of a cluster of galaxies. They reported that the density of dark matter declined significantly at radii $< r_s/3$ of the NFW halo profile after $\sim 10$ Gyr. The numerical tests reported in this Appendix reproduce their calculation.

Since EZ04 employed a 256$^3$ Cartesian grid, they restricted their calculation to the inner part of the NFW halo. They set the scale radius $r_s = 39$ mesh spaces, which implies that particles beyond a radius $r = 128 r_s/39 \approx 3.28 r_s$ could lie outside the grid. They therefore truncated the NFW halo at $r = 3.33 r_s$ and used a monopole approximation to integrate the motion of particles when they are off the grid. Their fiducial simulation uses $9 \times 10^6$ particles to represent the diffuse dark matter and 90 heavy particles to represent galaxies, which collectively have a mass that is 6% of the total. Both the dark matter particles and the heavy particles have initially the same spatial extent and isotropic velocities.

In their calculation, all forces were computed using the grid. Forces from a point mass on a Cartesian grid (shown graphically in the Appendix of Sellwood & Merritt (1994)) resemble those from the cubic spline kernel (Equation (4)) with a softening length of three grid spaces, or in their case $\epsilon = 3 r_s/39$.

Here, we reproduce this calculation using our own three-dimensional Cartesian grid code (Sellwood & Merritt 1994), demonstrate numerical convergence, and compare results from this grid with those from our spherical grid. As EZ04, we place all particles, both heavy and light, on the 257$^3$ grid where we set $r_s = 40$ mesh spaces. When using other grids, we compute interactions between the heavy particles (galaxies) and the light particles (dark matter) using expressions (2) and (3), in order to preserve a constant softening length in physical units ($\epsilon = 0.075 r_s$). We repeated the calculation with the same physical setup using grids of size 33$^3$, 65$^3$, and 129$^3$ to compute the self-interactions of the light particles, with the physical length scale $r_s = 5, 10,$ and 20 mesh spaces, respectively.

The results are shown in Figure 6; the initial density profile is shown by the black line and the profiles after $\sim 10$ Gyr on the various grids are shown by the colored lines. (The colored lines show time averages over an interval of $\pm 0.13$ Gyr, in order to obtain smooth curves.) The magenta line in Figure 6 also shows the result using the same physical model, but calculated using our high-resolution spherical grid. It is clear that the density reduction diminishes as the Cartesian mesh is refined, although the final density profile has almost converged at 257$^3$ and, reassuringly, this result agrees quite closely with that from our spherical grid. Furthermore, the final central density we obtain is very similar to that found by EZ04; the inner density in their model flattens to the value marked by the arrow.

We note that the results shown in Figure 6 can be compared with the $N_{\text{th}} = 150$ curve in Figure 5. The masses of the individual heavy particles are $0.67 \times 10^{-3}$ of the halo in both cases, but the halo concentrations differ, which affects the scaling with time. Since $c = 5.45$ for the cluster and $c = 15$ for the galaxies, the square root of the density ratios is $\approx 3.4$. Therefore, the cluster simulation is run for about one-third of the number of dynamical times of the galaxy, which also has more heavy particles. A comparison of the density profiles in the two

**Figure 6.** The initial (black) and final (color) density profiles of runs for comparison with EZ04, showing a convergence test with four different Cartesian grids and our spherical grid (magenta). The core density obtained by EZ04 is marked by the arrow.

(A color version of this figure is available in the online journal.)
simulations at equal numbers of dynamical times reveals very similar density changes, as it should. Thus, we confirm that a density reduction can indeed be obtained if the assumptions made by EZ04 hold. However, they invoked 90 massive galaxies in the inner part of the cluster, whereas the true number is probably less (Stanford et al. 2002). Furthermore, they implausibly assumed that the galaxies (heavy particles) have no dark halos, as acknowledged by Nipoti et al. (2004); more massive heavy particles will experience stronger friction, but as some dark matter is likely to be stripped from each galaxy’s halo, the change to the overall dark matter profile needs to be computed from more realistic simulations (e.g., Ma & Boylan-Kolchin 2004).

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