The Galaxy Disk in Cosmological Context
Proceedings IAU Symposium No. 254, 2008
J. Andersen, J. Bland-Hawthorn & B. Nordström, eds.

doi:10.1017/S1743921308027415

Dark Matter Density in Disk Galaxies

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Abstract. I show that the predicted densities of the inner dark matter halos in ΛCDM models of structure formation appear to be higher than estimates from real galaxies and constraints from dynamical friction on bars. This inconsistency would not be a problem for the ΛCDM model if physical processes that are omitted in the collisionless collapse simulations were able to reduce the dark matter density in the inner halos. I review the mechanisms proposed to achieve the needed density reduction.

Keywords. Stellar dynamics, galaxies: halos, dark matter

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1. Motivation

I was invited to review secular evolution in disk galaxies. Rather than attempt a very superficial review of this vast topic, I here focus on dynamical friction. Several other possible topics could be included in a review of secular evolution, such as: scattering of disk stars, which I reviewed only recently (Sellwood 2008a); mixing and spreading of disks (e.g. Sellwood & Binney 2002; Roškar *et al.* 2008; Freeman, these proceedings); and the formation of pseudo-bulges (e.g. Kormendy & Kennicutt 2004; Binney, these proceedings).

The current ΛCDM paradigm for galaxy formation (e.g. White, these proceedings) makes specific predictions for the dark matter (DM) densities in halos of galaxies. I first argue that halos of some barred galaxies are inconsistent with this prediction, and then consider whether DM halo densities could be lowered by internal galaxy evolution.

2. Inner Halo Density

Attempts to measure the halo density and its slope in the innermost parts of galaxies are beset by many observational and modeling issues (e.g. Rhee *et al.* 2004; Valenzuela *et al.* 2007), while the predictions from simulations in the same innermost region are still being revised, as shown earlier by White. It therefore makes sense to adopt a more robust measure of central density, such as that proposed by Alam, Bullock & Weinberg (2002). Their parameter, $\Delta_{v/2}$, is a measure of the mean DM density, normalized by the cosmic closure density, interior to the radius at which the circular rotational speed due the DM alone rises to half its maximum value. For those more familiar with halo concentrations, it is useful to note that for the precise NFW (Navarro, Frenk & White 1997) halo form, $\Delta_{v/2} = 672c^3/[\ln(1+c) - c/(1+c)]$, if c is defined where the mean halo density is 200 times the cosmic closure value; thus $\Delta_{v/2} \simeq 10^{5.5}$ for a $c = 9$ halo. However, a further advantage of $\Delta_{v/2}$ is that it is not tied to a specific density profile.

2.1. *Prediction*

Figure 1, reproduced from Macció, Dutton & van den Bosch (2008), shows the ΛCDM prediction (shaded) that results when the initial amplitude and spectrum of density

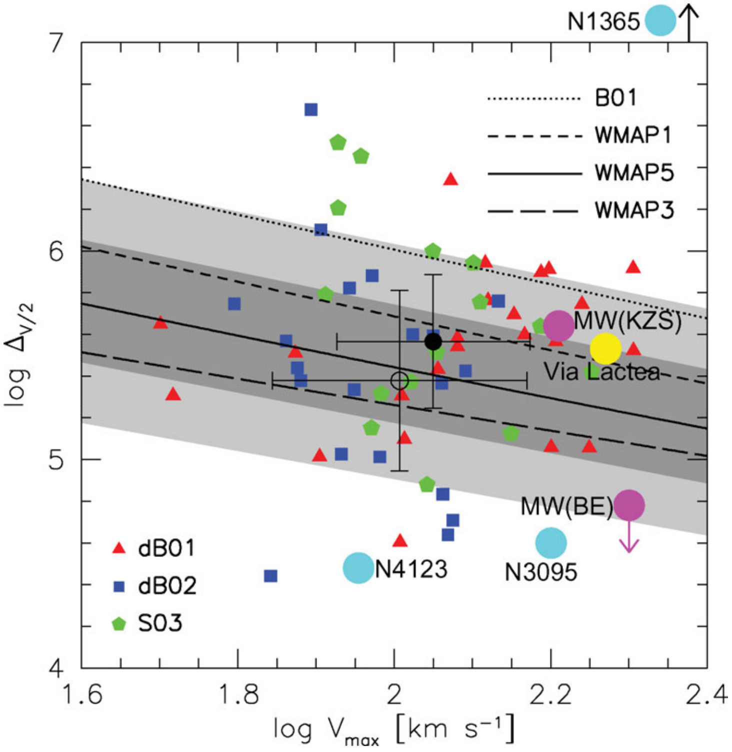

Figure 1. Figure reproduced from Macció *et al.* (2008, with permission), to which I have added the large labeled points that are described in the text. The shaded regions show the 1− and $2-\sigma$ ranges of the predicted values of $\Delta_{v/2}$, while the lines show the means, as functions of the maximum circular speed from the DM halos. The small colored symbols show various estimates of these parameters for dwarf and LSB galaxies estimated by Macció *et al.* from data in de Blok, McGaugh & Rubin (2001), de Blok & Bosma (2002), and Swaters *et al.* (2003).

fluctuations match the latest cosmic parameters, as determined by the WMAP team (Komatsu *et al.* 2008). I have added one further predicted point from the *Via Lactea* model (Diemand, Kuhlen & Madau 2007), which is argued to resemble a typical halo that would host a galaxy such as the Milky Way.

2.2. *Data from Galaxies*

Macció *et al.* plot the small colored triangles, squares and pentagons, which show estimates of $\Delta_{v/2}$ culled from the literature. The data are from dwarf and LSB galaxies, that are believed to be DM dominated and the large black circle indicates their mean in both coordinates, with the error bars indicating the ranges. The open circle with error bars shows a revised mean after subtracting a contribution to the central attraction by the estimated baryonic mass in these galaxies. These authors conclude that these data are consistent with the model predictions.

The large cyan circles are estimates for large galaxies: both NGC 4123 (Weiner, Sellwood & Williams 2001) and NGC 3095 (Weiner 2004) have well-estimated halos that are significantly below the predicted range. The inner density estimated for NGC 1365 (Zanmár Sanchéz *et al.* 2008), on the other hand, is $\Delta_{v/2} \sim 5 \times 10^7$, which is off the top of this plot, though the total halo mass is quite modest; a large uncertainty in the inclination, a possible warp that is very hard to model, together with evidence of a inner disturbance that required us to fit to data only one side of the bar, all conspire to render the inner halo density of this Fornax cluster galaxy quite uncertain.

I also plot two magenta points from different mass models for the Milky Way. The upper point is from Klypin, Zhao & Somerville (2002) while the lower shows the upper bound on the inner halo density estimated by Binney & Evans (2001). Their bound comes from trying to include enough foreground disk stars to match an old estimate (Popowski *et al.* 2001) of the micro-lensing optical depth to the red-clump stars of the Milky Way bulge; current estimates of this optical depth are somewhat lower (Popowski *et al.* 2005), suggesting a reanalysis will allow a higher halo density.

It is important to realize that the creation of a disk through condensation, or inflow, of gas into the centers dark halos must deepen the gravitational potential and cause the halo to contract (e.g. Blumenthal *et al.* 1986; Sellwood & McGaugh 2005). Thus, estimates of the current halo density should be reduced to take account of halo compression. Allowance for compression brings the point for NGC 1365 down by more than one order of magnitude. But making this correction for all the galaxies (which Macció *et al.* did not do for their open circle point) will move all the data points down, including the well-estimated points for NGC 4123 & NGC 3095 that are already uncomfortably low.

The only real difficulties presented by the comparison with the predictions in Fig. 1 arise from two well-determined low points, which could simply turn out to be anomalous. Additional evidence suggesting uncomfortably low DM densities in real galaxies comes from other rotation curve data (e.g. Kassin, de Jong & Weiner 2006) and the difficulty of matching the observed zero point of the Tully-Fisher relation (e.g. Dutton, van den Bosch & Courteau 2008). However, an independent argument, based on the constraints from dynamical friction on bars, also suggests that the DM density in barred galaxies is generally lower than predicted.

2.3. *Bar Slow Down*

Bars in real galaxies are generally believed to be “fast”, in that the radius of corotation is generally larger than the semi-major axis of the bar by only a small factor, $\mathcal{R}$. Indications that $1 \lesssim \mathcal{R} \lesssim 1.3$ come from (a) direct measurements in largely gas-free galaxies, summarized by Corsini (2008), (b) models of the gas flow (e.g. Weiner *et al.* 2001; Bissantz, Englmaier & Gerhard 2003), and (c) indirect arguments about the location of dust lanes (e.g. Athanassoula 1992). Rautiainen, Salo & Laurikainen (2008), and others, claim a few counter-examples from indirect evidence, although they concede that they try to match the morphology of the spiral patterns, which may rotate more slowly than the bar.

After some considerable debate, a consensus seems to be emerging that strong bars in galaxies should experience fierce braking unless the halo density is low (Debattista & Sellwood 1998, 2000; O’Neill & Dubinski 2003; Holley-Bockelmann, Weinberg & Katz 2005; Colín, Valenzeula & Klypin 2006). The counter-example claimed by Valenzuela & Klypin (2003) was shown by Sellwood & Debattista (2006) to have resulted from a numerical artifact in their code. The claims of discrepancies by Athanassoula (2003) are merely that weak, or initially slow bars, are less strongly braked, while she also finds that strong, fast bars slow unacceptably in dense halos.

Thus there is little escape from the conclusion by Debattista & Sellwood (2000), that the existence of fast bars in strongly barred galaxies requires a low density of DM in the inner halo. Our original constraint required near maximal disks, although the halo models in that paper were not at all realistic. Figure 2 summarizes the results from a new study of exponential disks embedded in NFW halos, computed using the code described in Sellwood (2003) that has greatly superior dynamic range. When scaled to the Milky

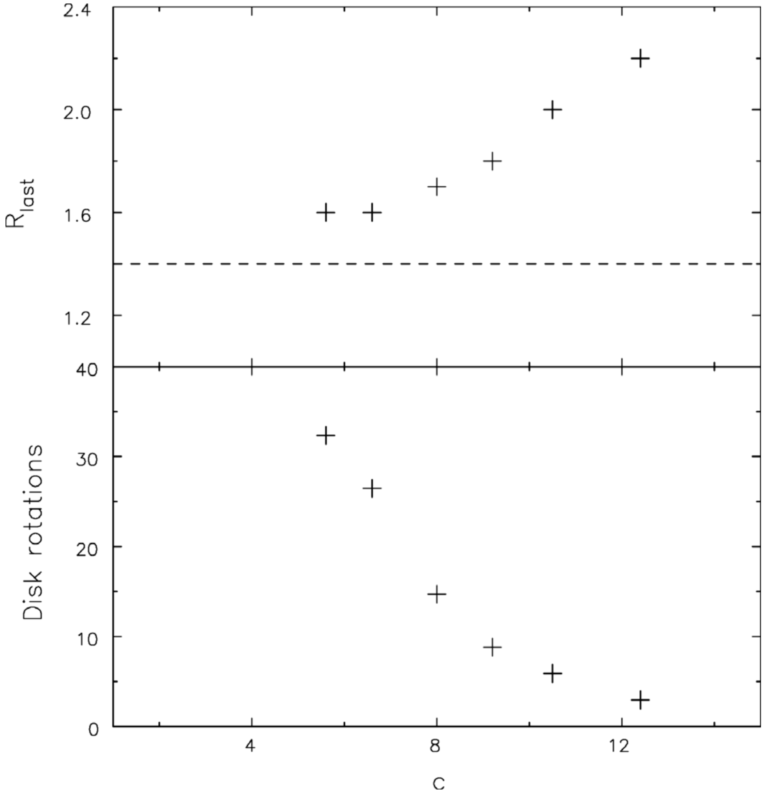

Figure 2. Bars in NFW halos. Above: The value of $\mathcal{R}$ at the time each simulation was stopped. Below: The number of disk rotations before the bar slowed to the point where $\mathcal{R} = 1.4$.

Way, a rotation period at 3 disk scale lengths in these models is 270 Myr. In all cases, the bar becomes slow by the end of the experiment, although the number of disk rotations needed until $\mathcal{R} > 1.4$ increases as the concentration index, c, is reduced. Thus, friction in NFW halos causes bars to become unacceptably slow in a few disk rotations when $c \gtrsim 10$, but on a time scale $\gtrsim 7.5$ Gyr when $c \lesssim 6$ or when the uncompressed $\Delta_{v/2} \lesssim 10^{5.1}$. This conservative bound would exclude well over half the predicted range of halo densities in Fig. 1 for an uncompressed $V_{\max} = 10^{2.25} \simeq 180$ km/s.

In the context of this symposium, it would be nice to test Milky Way models for bar slow-down. The halo and disk in the model tested by Valenzuela & Klypin (2003) were selected from the Klypin *et al.* (2002) models for the Milky Way. The simulations reveal that a very large bar with semi-major axis $\gtrsim 5$ kpc forms quickly, which slows unacceptably within ~ 5 Gyr. Unfortunately, the absence of a realistic bulge in these experiments crucially prevents these results from being regarded as a test of the Klypin *et al.* (2002) MW models, since a bulge should cause a much shorter and faster bar to form.

3. Can the DM Density Be Reduced?

The ΛCDM model would not be challenged if the present-day DM density in galaxies can be reduced by processes that are neglected in cosmic structure formation simulations, which generally follow the dynamics of collisionless collapse only. Four main ideas have been advanced that might achieve the desired density decrease.

3.1. *Feedback*

This first idea is not a secular effect, and therefore strictly falls outside my assigned topic. However, I discuss it briefly because it should not be omitted from any list of processes that might effect a density reduction.

The basic idea, proposed by Navarro, Eke & Frenk (1997), Binney, Gerhard & Silk (2001), and others is that gas should first collect slowly in a disk at the center of the halo, thereby deepening the gravitational potential well and compressing the halo adiabatically. A burst of star formation would then release so much energy that most of the gas would be blasted back out of the galaxy at very high speed, resulting in a non-adiabatic decompression of the halo, which may possibly result in a net reduction in DM density.

Gnedin & Zhao (2002) present the definitive test of the idea. In their simulations, they slowly grew a disk inside the halo, causing it to compress adiabatically, and then they instantaneously removed the disk. With this artifice, they deliberately set aside all questions of precisely how the star burst could achieve the required outflow, in order simply to test the extreme maximum that any conceivable feedback process could achieve.

They found that the final density of the halo was lower than the initial, confirming that the effect can work, and that mass blasted out from the very center of the potential has greatest effect, presumably because it produces the largest instantaneous change in the gravitational potential. However, density reductions by more than a factor of two required that the disk be unreasonably concentrated, and consequently the baryonic mass has to be blasted out from deep in the potential well.

3.2. *Bar-Halo Friction*

The same physical process that slows bars, discussed in §2.3, can also reduce the density of the material that takes up the angular momentum, as first reported by Hernquist & Weinberg (1992). This mechanism prompted Weinberg & Katz (2002) to propose the following sequence of events as a means to reconcile ΛCDM halo predictions with bar pattern speed constraints and other data. They argued that a large bar in the gas at an early stage of galaxy formation could reduce the DM density through dynamical friction. The gas bar would then disperse as star formation proceeded, so that were a smaller stellar bar to form later it would not experience much friction. Their idea has been subjected to intensive scrutiny.

Normal Chandrasekhar friction (e.g. Binney & Tremaine 2008, §8.1) is formally invalid in more realistic dynamical systems, such as quasi-spherical halos, because the background particles are bound to the system and will return to interact with the perturber repeatedly. Tremaine & Weinberg (1984) showed that under these circumstances angular momentum exchange occurs at resonances between the motion of the perturber and that of the background particles.

The N-body simulations mentioned in §2.3 generally did not produce a substantial reduction in halo density, despite the presence of strong friction. This could be because the bars were not strong enough, but Weinberg & Katz (2007a,b) argue that the simulations were too crude and that delicate resonances would not be properly mimicked in simulations unless the number of particles exceeds between 10^7 & 10^9, depending on the bar size and strength and the halo mass profile.

Thus two major questions arise: (1) are results from simulations believable? and (2) can realistic bars cause a large density decrease? I addressed both these issues in a recent

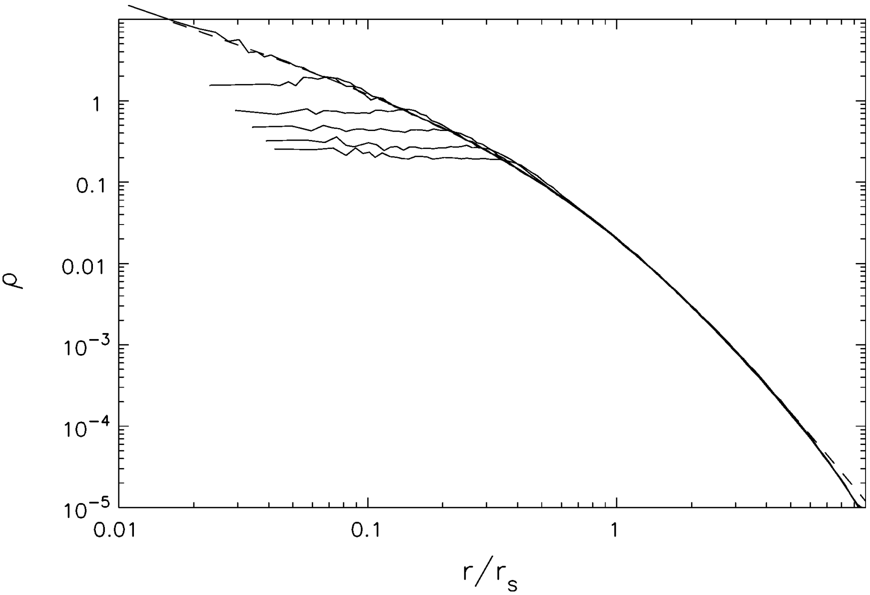

Figure 3. Results from five different experiments with different bar lengths. The dashed line shows the initial profile, while the solid lines show estimates from the particles of the initial (cusped) and final (cored) density profiles from a series of runs with different bar semi-major axes. The final density lines from the lowest to the highest are for bar lengths, $a/r_s = 1$, 0.8, 0.6, 0.4, & 0.2.

paper (Sellwood 2008b). While rigid, ellipsoidal bars are not terribly realistic, I used them deliberately in order to test the analysis and to compare with the simulations presented by Weinberg & Katz. Dubinski (these proceedings) presents results of similar tests using fully self-consistent disks that form bars.

3.2.1. *What N Is Enough?*

Simple convergence tests reveal that experiments with different numbers of particles converge to an invariant time evolution of both the pattern speed and halo density changes at quite modest numbers of halo particles. I report that $N = 10^5$ seemed to be sufficient for a very large bar, while $N \sim 10^6$ was needed for a more realistic bar. I observed no change the results in either case as I increased to $N = 10^8$, or when I employed a spectrum of particle masses in order to concentrate more into the crucial inner halo. I found results for different numbers of particles overlaid each other perfectly, with no evidence for the stochasticity that Weinberg & Katz predicted should result if few particles were in resonance.

I also demonstrated that my simulations did indeed capture resonant responses that converged for the same modest particle numbers. I measured the change in the density of particles $F(L_{\rm res})$, where $L_{\rm res}$ is an angular momentum-like variable that depends on orbit precession frequency. Using this variable, I was able to estimate that some 7% – 20% of halo particles participated in resonant angular momentum exchanges with the bar during a short time interval. This fraction is vastly greater than Weinberg & Katz predicted, because they neglected to take into account the broadening of resonances caused by the evolving bar perturbation, that both grows and slows on an orbital timescale. Athanassoula (2002) and Ceverino & Klypin (2007) also demonstrated the existence of resonances in their simulations.

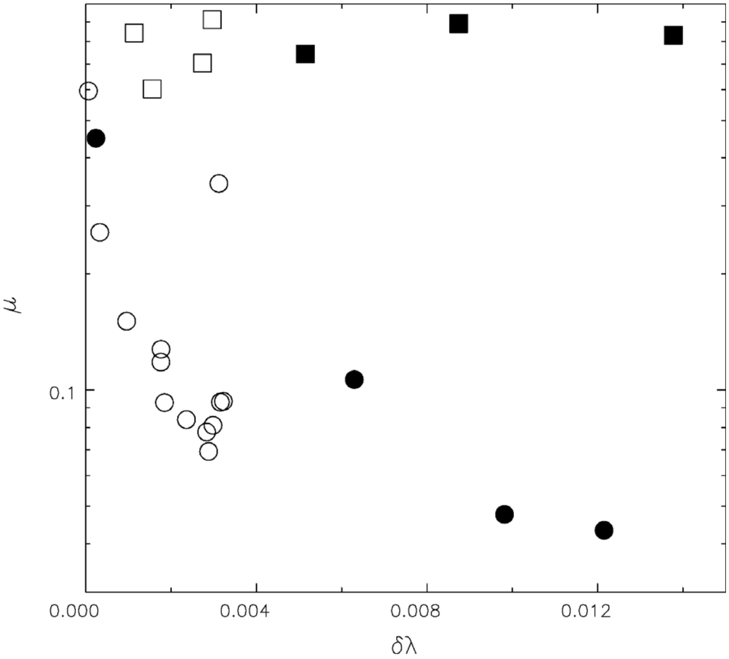

Figure 4. Fractional changes, μ, to $\Delta_{v/2}$ in many experiments. The abscissae show the angular momentum given to the halo, expressed as the usual dimensionless spin parameter. Open circles mark results from experiments in which the density profile of the inner cusp was flattened, while squares indicate experiments where cusp flattening did not occur. Filled symbols show results from experiments in which the moment of inertia of the bar was increased by a factor 5 in all cases except the point at the upper right, where the MoI was increased 10-fold (for more details see Sellwood 2008). The changes to $\Delta_{v/2}$ make no allowance for halo compression.

3.2.2. *Density Reduction by Very Strong Bars*

Figure 3 shows that a strong bar rotating in a halo within a density cusp ($\rho \propto 1/r$) can flatten the cusp to $\sim 1/3$ bar length. The rigid bar needed to accomplish this must have an axis ratio $a/b \gtrsim 3$, a mass $M_b \gtrsim 30\%$ of the halo mass inside $r = a$.

While cusp flattening is a driven response caused by the slowing bar, it is also a collective effect. I find a much smaller change when I hold fixed the monopole terms of the halo self-gravity. Thus it is dangerous, when studying halo density changes, to include any rigid mass component.

The only simulation I am aware of in which a self-consistent bar flattened the inner density cusp is that reported by Holley-Bockelmann *et al.* (2005). They report a significant density reduction that flattened the cusp to a radius $\sim a/5$. Note that in their model, the initial halo density was not compressed by the inclusion of the disk, since they rederived the halo distribution function that would be in equilibrium in the potential of an uncompressed NFW halo plus the disk.

3.2.3. *More Gradual Changes*

A number of other simulations in the literature have revealed a modest density reduction caused by angular momentum exchange with a bar in the disk. e.g. Debattista & Sellwood (2000) show a reduction in the halo contribution to the central attraction, and something similar can also be seen in Athanassoula's (2003) simulations. None of these models included very extensive halos.

The inner halo density in fully self-consistent simulations with more extensive and cusped halos can actually rise as the model evolves (Sellwood 2003; Colín *et al.* 2006). This happens because angular momentum lost by the bar in the disk causes it to contract; the deepening potential of the disk causes further halo compression that overwhelms any density reduction resulting from the angular momentum transferred to the halo.

3.2.4. *Angular Momentum Reservoir*

A crucial consideration that limits the magnitude of halo density reduction by bar friction is the total angular momentum available in the baryonic disk. Tidal torques in the early universe lead to halos with a log-normal distribution of spin parameters with a mean $\lambda \sim 0.05$, where the dimensionless spin parameter is $\lambda = LE^{1/2}/GM^{5/2}$ as usual. Assuming that the baryons and dark matter are well mixed initially, the fraction of angular momentum in the baryons is equal to the baryonic mass fraction in the galaxy: some 5% – 15%. Thus total angular momentum loss from the disk could increase the halo spin parameter by typically $\delta\lambda \sim 0.005$.

Figure 4, taken from Sellwood (2008b), shows the factor by which the halo density is reduced, $\mu = \Delta_{v/2,\mathrm{fin}}/\Delta_{v/2,\mathrm{init}}$ as the ordinate against the angular momentum gain of halo. A density reduction by a factor of 10 is possible, but the bar must be extreme, having a semi-major axis, a, approaching that of the break radius, r_s, of the NFW profile and a mass $> 30\%$ halo interior to $r = a$. Furthermore, such a density reduction is achieved at the expense of removing a large fraction of the angular momentum of the baryons. It should also be noted that the density changes shown in Fig. 4 also do not take account of any halo compression that might have occurred as the bar and disk formed.

3.3. *Baryonic Clumps*

El-Zant, Shlosman & Hoffman (2001) proposed that dynamical friction from the halo on moving clumps of dense gas will also transfer energy to the DM and lower its density. They envisaged that baryons would collect into clumps through the Jeans instability as galaxies are assembled and present somewhat simplified calculations of the consequences of energy loss to the halo. The idea was taken up by Mo & Mao (2004), who saw this as a means to erase the cusps in small halos before they merge to make a main galaxy halo, and by Tonini, Lapi & Salucci (2006).

The proposed mechanism has a number of conceptual problems, however. The model assumes that the settling gas clumps maintain their coherence for many dynamical crossing times without colliding with other clumps or being disrupted by star formation, for example. In addition, calculations (e.g. Kaufmann *et al.* 2006) of the masses of condensing gas clumps suggest they range up to only $\sim 10^6\ M_\odot$, which is too small to experience strong friction. Larger clumps will probably gather in subhalos, which may get dragged in, but simulations with sub-clumps composed of particles (e.g. Ma & Boylan-Kolchin 2004) indicate that the DM halos of the clumps will be stripped, which simply replaces any DM moved outwards in the halo. Debattista *et al.* (2008) suggest halo compression is an issue here also, but the essential idea suggested by El-Zant *et al.* is to displace the DM as the gas settles, which avoids halo compression.

3.3.1. *A Direct Test*

Setting all these difficulties to one side, Jardel & Sellwood (2008) set out to test the mechanism with N-body simulations. As proposed by El-Zant *et al.*, we divided the entire mass of baryons into N_h equal mass clumps, treated as softened point masses, to which we added isotropic random motion to make their distribution in rough dynamical equilibrium

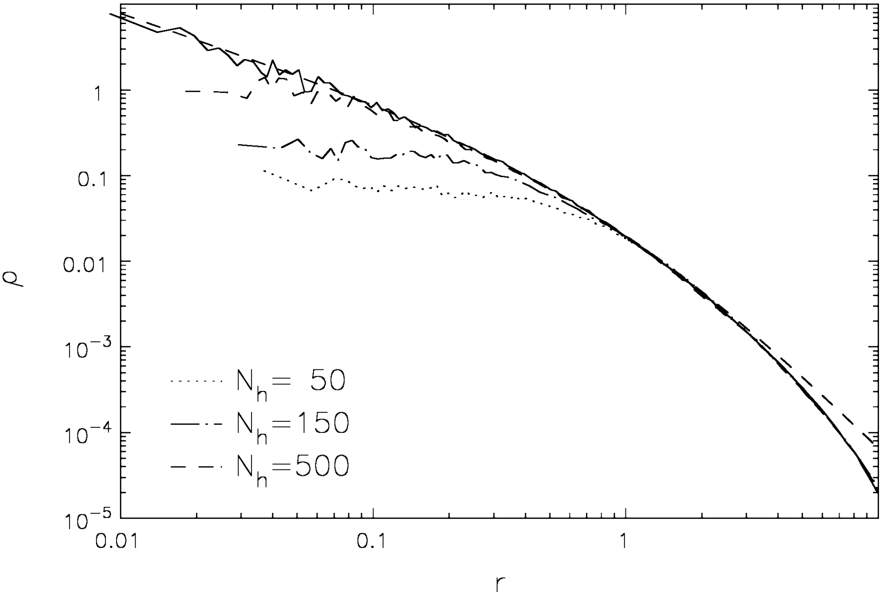

Figure 5. The changes in density caused by the settling of N_h heavy particles with total mass of $0.1 M_{200}$, initially distributed at uniform density within a sphere of radius $4rs$ in an NFW halo. The solid line shows the density measured from the particles at the start while the broken lines show the density after 9 Gyr. Another dashed line shows the corresponding theoretical NFW curve.

inside an NFW halo composed of $\sim 1\,\mathrm{M}$ self-gravitating particles. All particles, both light and heavy, experienced the attraction of all others.

Figure 5 shows results after $\sim$ 9 Gyr, when scaled to a $c = 15$ halo – the timescale would be even longer for less concentrated halos. We find that some density reduction does occur, but the rate at which the density is decreased is considerably slower than El-Zant *et al.* predict. We traced this discrepancy to their use of three times too large a Coulomb logarithm in their calculations.

Fig. 5 also shows that the rate of density reduction rises as the baryon mass is concentrated into fewer, more massive particles. Again our result is consistent with that of Ma & Boylan-Kolchin (2004), who employed a mass spectrum of clumps, and who showed that a much smaller density reduction occurred in a separate simulation that omitted the three heaviest clumps. Thus, if this process is to work on an interesting time-scale, it requires a few gas clumps whose masses exceed 1% of the entire halo.

Mashchenko *et al.* (2006, 2007) argue that the energy input to the halo, mediated by the motion of the mass clumps, can be boosted if the gas is stirred by stellar winds and supernovae – a less extreme form of feedback (*cf.* §3.1). Their simulations of the effect reveal a density reduction in dwarf galaxies. Peirani *et al.* (2008), on the other hand, propose AGN activity to accelerate gas clumps. They present simulations that show the cusp can be flattened to $\sim 0.1 r_s$ with a clump having mass of $\sim$ 1% of the galaxy mass, being driven outwards from the center to a distance of half the NFW break radius at a speed of 260 km/s. In both these models, it is unclear how the dense material can be accelerated to the required speed (e.g. MacLow & Ferrara 1999).

3.4. *Recoiling/Binary BHs*

In any hierarchical structure-formation model, halos grow through a succession of mergers (e.g. Wechsler *et al.* 2002). If massive black holes (BHs) have formed in the centers of two galaxies that merge, then one expects both BHs to settle to the center of the merged halo and to form a binary pair of BHs in orbit about each other. The physics of the decay of the orbit is interestingly complicated (e.g. Merritt & Milosavljević 2005).

The star density in the centers of elliptical galaxies can be reduced by star scattering as the BH binary hardens, and also by the separate process of BH recoil if the binary encounters another massive object. Merritt & Milosavljević (2005) point out that the star density can be significantly reduced only within the sphere of gravitational influence of the BHs, which extends to $r \sim r_h$, where $r_h = GM_\bullet/\sigma^2$, where $M_\bullet$ is the mass of the BH and σ is the velocity dispersion of the stars. Generous values for disk galaxies might be $M_\bullet = 10^7 M_\odot$ and $\sigma = 100$ km/s, yielding $r_h \simeq 4.4$ pc.

Since none of the processes that affect the star density in the center depend upon the masses of the individual stars, DM particles will be affected in a similar manner, and we must expect the DM density to be depleted also over the same volume. However, because black hole dynamics affects only the inner few parsecs, it can have essentially no effect on bar pattern speed constraints or values of parameters such as $\Delta_{v/2}$.

4. Conclusions

The inner densities of DM halos of galaxies today continue to challenge the ΛCDM model for galaxy formation. Both direct estimates in a few galaxies, and dynamical friction constraints from bar pattern speeds require inner densities lower than predicted in DM-only simulations by at least a factor of a few.

Several processes that are omitted from DM only simulations can reduce the inner halo density. Feedback has a very slight effect unless a large mass of gas is blasted out from the deepest point in the peotential well. Bar friction requires an extreme bar and removes a large fraction of the angular momentum in the baryons. Dynamical friction on massive gas clumps is too slow, unless moving gas clumps exceed $\sim 1\%$ of total baryonic mass. Scattering by merging or recoiling BHs affects only very center. Thus any of the four suggested mechanism needs to be stretched if it is to cause a significant reduction.

Acknowledgements

I thank Victor Debattista for comments on the manuscript and the organizers of the conference for travel support. This work was supported by grants AST-0507323 from the NSF and NNG05GC29G from NASA.

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A packed lecture hall listens to Jerry Sellwood's review.

James Bullock spellbinding his audience.