THE EFFECT OF BARYONS ON HALO SHAPES

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Abstract. Observational evidence indicates a mismatch between the shapes of collisionless dark matter (DM) halos and those of observed systems. Using hydrodynamical cosmological simulations we investigate the effect of baryonic dissipation on halo shapes. We show that dissipational simulations produce significantly rounder halos than those formed in equivalent dissipationless simulations. Gas cooling causes an average increase in halo principal axis ratios of \(\sim 0.2 - 0.4\) in the inner regions and a systematic shift that persists out to the virial radius, alleviating any tension between theory and observations. Although the magnitude of the effect may be overestimated due to overcooling, cluster formation simulations designed to reproduce the observed fraction of cold baryons still produce substantially rounder halos. Subhalos also exhibit a trend of increased axis ratios in dissipational simulations. Moreover, we demonstrate that subhalos are generally rounder than corresponding field halos even in dissipationless simulations. Lastly, we analyze a series of binary, equal-mass merger simulations of disk galaxies. Collisionless mergers reveal a strong correlation between DM halo shape and stellar remnant morphology. In dissipational mergers, the combination of strong gas inflows and star formation leads to an increase of the DM axis ratios in the remnant. All of these results highlight the vital role of baryonic processes in comparing theory with observations and warn against over-interpreting discrepancies with collisionless simulations on small scales.

1 Introduction

The hierarchical, cold dark matter (CDM) model of cosmological structure formation successfully explains a plethora of observations on large scales, where linear theory is adequate (e.g., Spergel et al. 2003). However, on non-linear scales several issues remain unresolved. One intriguing discrepancy concerns the shapes of dark
matter (DM) halos. *Dissipationless* cosmological *N*-body simulations consistently produce halos with minor-to-major axis ratios in the range \( \langle c/a \rangle \simeq 0.5 \pm 0.2 \) and projected ellipticities of \( \epsilon \sim 0.4 - 0.5 \) (e.g., Jing & Suto 2002, JS02). Inferring halo shapes observationally is a daunting task, yet a variety of probes exists that may enable us to distinguish between spherical and flattened halos (e.g., Merrifield 2004). In the Milky Way, flaring of the HI disk and the coherence of the Sagittarius tidal stream both imply a nearly spherical inner halo with \( c/a \sim 0.7 - 0.9 \) (e.g., Olling & Merrifield 2000; Ibata et al. 2001). In other systems, the ellipticities of galaxies and clusters inferred from X-ray and optical isophotes (e.g., Buote & Canizares 1996) and galaxy halos in weak lensing measurements (Hoekstra et al. 2004) are generally in the range \( \epsilon \sim 0.2 - 0.3 \).

Applying halo shapes as a cosmological test requires improvements in theoretical predictions. In this study, we investigate the effect of the dissipative infall of gas during galaxy formation on the shapes of halos and subhalos using high-resolution, cosmological simulations in the \( \Lambda \)CDM cosmology. For the first time, we consider the effect of baryons on halo shapes in high-resolution gasdynamical binary merger simulations between multicomponent galaxies that include radiative cooling and star formation.

## 2 Shapes of dark halos in cosmological simulations

In this section, we analyze cosmological simulations of 8 cluster-size systems and one galaxy-size system in a flat \( \Lambda \)CDM cosmology. For each system, we perform two sets of simulations starting from the same initial conditions but including different physical processes. The first set follows the dynamics of gas “adiabatically”, without radiative cooling. The second set includes gas cooling, star formation, metal enrichment, thermal supernovae feedback, and UV heating by an ionizing background. All cosmological simulations were performed with the Adaptive Refinement Tree code (Kravtsov 1999). For details on the simulations we refer the reader to Kazantzidis et al. (2004). We determine principle axis ratios \( b/a \) and \( c/a \) \((a \geq b \geq c)\) in differential radial bins using the modified inertia tensor (Dubinski & Carlberg 1991) as described in detail in Kazantzidis et al. (2004).

Figure 1 summarizes our results. The top panel shows the average change in the axis ratios of DM in cooling and adiabatic runs \([\text{e.g., } \Delta(b/a) \equiv (b/a)_{\text{cool}} - (b/a)_{\text{adiab}}]\) as a function of radius for all cosmological simulations. In the inner regions of halos, gas cooling increases axis ratios by \( \sim 0.4 \) at \( 0.1r_{\text{vir}} \) and by \( \sim 0.2 - 0.3 \) at \( 0.3r_{\text{vir}} \). The difference decreases with radius, but persists out to the virial radius. In the bottom panels, we present the distribution of subhalo shapes in the simulated clusters. The subhalo axis ratios we quote are based on particles within one half of the subhalo tidal radius, \( r_t \), and we analyzed only subhalos resolved with \( \geq 200 \) particles within \( r \leq 0.5r_t \). The masses of subhalos selected by these criteria range roughly from \( 10^{11.3} - 10^{12.5} h^{-1}M_\odot \). We show for comparison the shape distribution of collisionless field halos for similar masses from JS02 (solid line). First, subhalos in dissipationless cosmological simulations are considerably rounder than field halos, a result also reported by Moore et al. (2004). Second,
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**Fig. 1.** Top panel: The average difference between axis ratios in cooling and adiabatic cosmological simulations as a function of radius in units of the virial radius, \( r_{\text{vir}} \). The error bars correspond to the error on the mean value of \( \Delta(b/a) \) in each bin. The errors in \( \Delta(c/a) \) are similar. Bottom panels: The distribution of axis ratios for subhalos in the simulated clusters. The left panel shows the distribution of intermediate-to-major axis ratio, \( b/a \), and the right panel shows the minor-to-major axis ratio, \( c/a \), distribution. Solid lines are for adiabatic simulations while dashed lines are for dissipational simulations. The thin, solid lines in the right panel show the distribution of \( c/a \) for field halos using the fitting function of JS02, for four different masses indicated in the panel. The downward arrows show axis ratios of three host halos with \( M_{\text{vir}} \approx 10^{12} \ h^{-1} \ M_\odot \) and with \( \sim 10^{6} \) particles within their virial radii analyzed by Zentner et al. (2005).

Dissipational simulations predict rounder subhalos with a much more narrowly-peaked distribution of axis ratios.

In the CDM paradigm, galaxies form from the condensation of baryons in halo
Fig. 2. Principal axis ratios $b/a$ (thin lines) and $c/a$ (thick lines) of DM as a function of radius in units of $r_{\text{vir}}$ for one of the Virgo-size clusters. Solid lines correspond to the adiabatic simulation, while the dotted lines show the results of the simulation with radiative cooling. The dashed lines show the DM shape profile in a simulation with cooling artificially turned off at $z \leq 2$, resulting in a cold baryon fraction similar to that in observed galaxy clusters.

centers. As the central baryonic concentration grows and forms a disk or a spherical system, the overall mass distribution becomes more centrally concentrated and the central potential becomes rounder. The box orbits of DM particles in the central parts that serve as the backbone of a triaxial mass distribution, adjust to the presence of this rounder potential and are changing into less elongated forms (e.g. Gerhard & Binney 1985). In a few crossing times, most of the remaining box orbits will be destroyed as the overall potential becomes rounder. This transformation of orbital families drives halos to a more spherical shape, even at large radii, as our simulations demonstrate.

2.1 Halo shapes and the overcooling problem

Current hydrodynamical cosmological simulations of clusters may suffer from the “overcooling” problem: the predicted fraction of cold baryons (stars and cold gas) $f_{\text{cold}}$, is a factor of $\sim 2 - 3$ higher than observed (Lin et al. 2003). Indeed, in our simulated clusters $f_{\text{cold}} \sim 0.3 - 0.4$, a factor of $\geq 2$ higher than observed for systems in the mass range we consider. Thus, the effect of dissipation on halo shapes may be overestimated.

To assess the extent of the problem, we repeated one of the cluster simulations with radiative cooling artificially turned off at $z \leq 2$. This simulation was designed to reproduce the observed value of $f_{\text{cold}} \approx 14\%$ at $z = 0$. Figure 2 shows the DM axis ratio profiles for the three different runs. The effect of dissipation in the simulation with radiative cooling turned off is smaller than in the original simulation, as fewer baryons condense in the center, yet the shape of the DM distribution is still considerably more spherical than in the adiabatic run. This
result suggests that the effect of gas cooling on halo shapes is substantial even in simulations with realistic cold baryon fractions.

3 Shapes of dark halos in merger simulations

In this section, we analyze high-resolution simulations of binary equal-mass mergers of disk galaxies including different physical processes. We simulate purely collisionless mergers and mergers in which we follow the gas dynamics adiabatically. A third set of simulations includes radiative cooling, while in a fourth set we also incorporate star formation. We construct galaxy models using the technique of Hernquist (1993) with structural parameters consistent with standard ΛCDM (Mo et al. 1998). Each galaxy consists of a spherical and isotropic Navarro et al. (1996) DM halo and an exponential stellar disk, and may contain a spherical, Hernquist (1990) bulge and/or an exponential gaseous disk. The dark halo mass and total disk mass are constant in all initial galaxy models. We considered collisions on parabolic orbits with two encounter geometries (randomly-inclined and coplanar disk orientations), two values for the gas fraction (10% and 50% of the total disk mass), and two values for the disk thickness. All merger simulations were performed with the GASOLINE TreeSPH N-body code (Wadsley et al. 2004). For further details on the merger simulations we refer the reader to Kazantzidis et al. (2004) and Kazantzidis et al. (2005).

In the top panels of Figure 3, we present radial profiles $b/a$ and $c/a$ for remnants in collisionless, equal-mass binary merger simulations of halos with embedded stellar disks. For comparison we also show results of a DM halo-only merger. Inclined disk mergers produce nearly spherical stellar remnants, while coplanar mergers yield a disk-like stellar remnant with $c/a \sim 0.3$. The corresponding DM distribution is also more spherical in the inclined disk merger. However, in an inclined disk merger with the same orbital parameters as before, but with a factor of three thicker stellar disks, we find that the stellar remnant becomes less spherical and the halo axis ratios are lower by $\sim 0.15$ in the inner regions. These results indicate that the shape of the stellar remnant is sensitive to the mutual orientation and internal properties of the merging disks. The presence of a stellar remnant modifies the potential in the central region, where stars dominate gravitationally, and consequently affects the shape of the DM distribution.

The lower panels of Figure 3 show results for collisionless and hydrodynamical equal-mass, binary merger simulations of disk galaxies containing bulges. Dissipational mergers lead to an increase in axis ratios of DM that sensitively depends on the details of gas physics included in the simulations. The largest increase occurs in dissipational simulations which exhibit the deepest central potentials. In the adiabatic simulations, axis ratios are close to those of the collisionless runs because the gas is too hot ($T > 10^5$ K) to build up a significant central mass concentration. Since the DM responds to the total baryonic density enhancement DM axis ratios are similar in all dissipational mergers.
4 Conclusions

The dissipative infall of gas during galaxy formation alleviates the discrepancy between the shape distribution of collisionless DM halos and that of observed systems. Using high-resolution cosmological simulations we show that halos in simulations with radiative cooling are considerably more spherical than those in
dissipationless simulations. Dissipation results in an average increase in principal axis ratios of halos by $\sim 0.2 - 0.4$ in the inner regions. The difference decreases slowly with radius but remains substantial even at the virial radius. Subhalos also exhibit a similar trend of increased axis ratios in dissipational simulations and are generally rounder than corresponding field halos. We also showed that in an ad hoc cluster formation simulation designed to reproduce the observed cold baryon fraction, the DM halo is still notably rounder at all radii compared to its dissipationless counterpart, suggesting that our results are robust despite any issues of overcooling in simulated clusters.

In hierarchical CDM models of structure formation, halos grow during periods of slow accretion, when gas cools and condenses toward the center, and sequences of violent mergers. We performed a comprehensive series of collisionless and gas-dynamical binary merger simulations between disk galaxies to study the effect of baryons on the shape of the remnant DM distributions. Collisionless simulations indicate a strong correlation between the shape of the stellar remnant and DM halo shape. In dissipational mergers, strong gas inflows and star formation drive the remnant DM distribution to be significantly more spherical. All of the results reported in this study underscore the crucial role of baryonic processes in comparing the small scale predictions of the ΛCDM paradigm with observations.

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