DARK MATTER SUBSTRUCTURE WITHIN GALACTIC HALOS

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ABSTRACT

We use numerical simulations to examine the substructure within galactic and cluster mass halos that form within a hierarchical universe. Clusters are easily reproduced with a steep mass spectrum of thousands of substructure clumps that closely matches observations. However, the survival of dark matter substructure also occurs on galactic scales, leading to the remarkable result that galaxy halos appear as scaled versions of galaxy clusters. The model predicts that the virialised extent of the Milky Way’s halo should contain about 500 satellites with circular velocities larger than Draco and Ursa-Minor i.e., bound masses $\gtrsim 10^8 M_\odot$ and tidally limited sizes $\gtrsim 1 \text{kpc}$. The substructure clumps are on orbits that take a large fraction of them through the stellar disk leading to significant resonant and impulsive heating. Their abundance and singular density profiles has important implications for the existence of old thin disks, cold stellar streams, gravitational lensing and indirect/direct detection experiments.

\textit{Subject headings:} dark matter — cosmology: observations, theory — galaxies: clusters, formation

1. INTRODUCTION

The growth of structure in the universe by hierarchical accretion and merging of dark matter halos is an attractive and well motivated cosmological model (White & Rees 1978, Davis et al. 1985). The gravitational clustering process is governed by the dark matter component and the baryons only play a minor role. The idea that galaxies are defined as those objects where gas can quickly cool predates the current hierarchical model (Hoyle 1953), and has been invoked to set the scale for survival versus disruption (Rees & Ostriker 1977, White & Rees 1978).

It has proved difficult to compare the predictions of this model with non-linear structures, such as the internal properties of galaxy clusters. Numerical simulations had ubiquitously failed to find surviving substructure or “halos orbiting within halos” (e.g. Katz & White 1993, Summers et al. 1995, Frenk et al. 1996). It was generally thought that the so called “over-merging” problem could be overcome by the inclusion of baryonic component to increase the potential depth of galactic halos.

Analytic work suggested that over-merging was due entirely to poor spatial and mass resolution (Moore, Katz & Lake 1996). This has been verified by higher resolution simulations of clusters in which galactic halos survive without any inclusion of gas dynamics (Moore et al. 1998, Ghigna et al. 1998, Klypin et al. 1998). When a galaxy and its dark matter halo enter a larger structure, the outer regions are stripped away by the global tides and mutual interactions. The central region survives intact so that a galaxy may continue to be observed as a distinct structure within a cluster, with its own truncated dark matter halo (Natarajan et al. 1998).

In a hierarchical universe, galaxies form by a similar merging and accretion process as clusters (Klypin et al. 1999). Over-merging on galactic scales is a necessary requirement otherwise previous generations of the hierarchy would preclude the formation of disks. Observations suggest that over-merging has been nearly complete on galactic scales. The Milky Way contains just 11 satellites within its virial radius with $\sigma_{satellite}/\sigma_{halo} > 0.07$, i.e. that is equivalent to $\sigma_{satellite} = 10 \text{ km s}^{-1}$ (c.f. Mateo 1998 and references within). The same velocity dispersion ratio in a cluster corresponds to counting galaxies more massive than the Large Magellanic Clouds $\sigma_{LMC} \sim 50 \text{ km s}^{-1}$; there are 500-1000 such systems in a rich cluster (Bingelli et al. 1985, Driver et al. 1999). The same discrepancy exists at higher masses. The Coma cluster contains $\gtrsim 30$ galaxies brighter than the characteristic break in the luminosity function, $L_* = \sigma > 200 \text{ km s}^{-1}$ (Lucey et al. 1991). Scaling this limit to a galaxy halo we find just 2 satellites in the Milky Way or 3 near Andromeda.

Why should substructure be destroyed in galactic halos but not in clusters? Analytic calculations suggested that galaxies should contain more satellites than observed (Kauffmann et al. 1993). The shape of the power spectrum varies over these scales such that galaxies form several billion years before clusters and the mass function of their progenitor clumps may differ. Furthermore, as the power spectrum asymptotically approaches a slope of -3, clumps of all masses will be collapsing simultaneously and the timescale between collapse and subsequent merging becomes shorter. These effects may conspire to preferentially smooth out the mass distribution within galactic halos. In this letter we use numerical simulations to study the formation of galactic halos with sufficient force and mass resolution that can resolve satellites as small as Draco. This allows us to make a comparative study with observations and simulations of larger mass halos.

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2. SUBSTRUCTURE WITHIN GALAXIES AND CLUSTERS

We simulate the hierarchical formation of dark matter halos in the correct cosmological context using a high resolution parallel treecode pkdgrav. An object is chosen from a simulation of an appropriate cosmological volume. The small scale waves of the power spectrum are realised within the volume that collapses to this object with progressively lower resolution at increasing distances from the object. The simulation is then re-run to the present epoch with the higher mass and force resolution. We have applied this technique to several halos identified from a $10^6\,\text{Mpc}^3$ volume, including a cluster similar to the nearby Virgo cluster (Ghigna et al. 1998) and a galaxy with a circular velocity and isolation similar to the Milky Way.

The cosmology that we investigate is a universe dominated with a critical density of cold dark matter, normalised to reproduce the local abundance of galaxy clusters. The important numerical parameters to remember are that each halo contains more than one million particles within the final virial radius $r_{\text{vir}}$, and we use a force resolution $\sim 0.1 r_{\text{vir}}$. Further details of computational techniques and simulation parameters can be found in Ghigna et al. (1998) and Moore et al. (1999). Here we focus our attention directly on a comparison with observations.

Figure 1 shows the mass distribution at a redshift $z = 0$ within the virial radii of our simulated cluster and galaxy. It is virtually impossible to distinguish the two dark matter halos, even though the cluster halo is nearly a thousand times more massive and forms 5 Gyrs later than the galaxy halo. Both objects contain many dark matter substructure halos. We apply a group finding algorithm to extract the sub-clumps from the simulation data and use the bound particles to directly measure their kinematical properties: mass, circular velocity, radii, orbital parameters (c.f. Ghigna et al. 1998). Although our simulations do not include a baryonic tracer component, we can compare the properties of these systems with observations using the Tully-Fisher relation (Tully & Fisher 1977). This provides a simple benchmark for future studies that incorporate additional physics such as cooling gas and star-formation.

![Figure 1](image1.png)

**Fig. 1.** The density of dark matter within a cluster halo of mass $5 \times 10^{14} \, M_\odot$ (upper) and a galaxy halo of mass $2 \times 10^{12} \, M_\odot$ (lower). The edge of the box is the virial radius, 300 kpc for the galaxy and 2000 kpc for the cluster (peak circular velocities of 200 km s$^{-1}$ and 1100 km s$^{-1}$ respectively).

![Figure 2](image2.png)

**Fig. 2.** The abundance of cosmic substructure within our Milky Way Galaxy, the Virgo cluster and our models of comparable masses. We plot the cumulative numbers of halos as a function of their circular velocity ($v_c = \sqrt{GM_b/r_b}$), where $m_b$ is the bound mass within the bound radius $r_b$ of the substructure, normalised to the circular velocity, $V_{\text{global}}$, of the parent halo that they inhabit. The dotted curve shows the distribution of the satellites within the Milky Way’s halo (Mateo 1998) and the open circles with Poisson errors is data for the Virgo galaxy cluster (Binggeli et al. 1985). We compare these data with our simulated galactic mass halo (dashed curves) and cluster halo (solid curve). The second dashed curve shows data for the galaxy at an earlier epoch, 4 billion years ago, dynamical evolution has not significantly altered the properties of the substructure over this timescale.

Figure 2 shows the observed mass (circular velocity) function of substructure within the Virgo cluster of galaxies compared with our simulation results. The circular velocities of substructure halos are measured directly from
the simulation, whilst for the Virgo cluster we invert the Binggeli et al. luminosity function data using the Tully-Fisher relation. There are no free parameters to this fit. The overall normalization of the simulation was fixed by large scale clustering properties and we then picked a cluster from a low resolution run that had a dispersion similar to Virgo. We count as a remarkable success that this model reproduces both the shape and amplitude of the galaxy mass function within a cluster.

Also plotted in Figure 2 is the cumulative distribution of the 11 observed satellites that lie within 300 kpc of the Milky Way. Where necessary we have converted 1d velocity dispersions to circular velocities assuming isotropic velocity distributions. The model over-predicts the total number of satellites larger than the dSph’s by about a factor of 50.

The distribution of circular velocities for the model galaxy and cluster can be fitted with a power law $n(v/V_{vir}) \propto (v/V_{vir})^{-4}$, similar to that found by Klypin et al. (1999) for satellites in the proximity to galactic halos. The mass function within these systems can be approximated by a power law with $n(m/M_{vir}) \propto (m/M_{vir})^{-2}$. The tidally limited substructure halos have profiles close to isothermal spheres with core radii equal to our resolution length - increasing the resolution only makes the halos denser and more robust to disruption (Moore et al. 1998).

3. DISCUSSION

Either the hierarchical model is fundamentally wrong, or the substructure lumps are present in the galactic halo and contain too few baryons to be observed. The deficiency of satellites in galactic halos is similar to a deficiency of dwarf galaxies in the field (e.g. Kauffmann et al. 1993). One possibility is that some of the missing satellites may be linked to the high velocity clouds (Blitz et al. 1999). Numerous studies have invoked feedback from star formation or an ionizing background to darken dwarfs by expelling gas and inhibiting star formation in low mass halos (Dekel & Silk 1986; Quinn, Katz & Efstathiou 1996). The case for feedback has always been weak. Galaxies outside of clusters are primarily rotationally supported disks, their final structure has clearly been set by their angular momentum rather than a struggle between gravity and winds. The strongest star-bursts seen in nearby dwarf galaxies lift the gas out of their disks, but the energy input is insufficient to expel the gas and reshape the galaxy (Martin 1998).

While there might be little consequence to darkening dwarfs in the field, spiral disks will neither form nor survive in the presence of large amounts of substructure. The strongly fluctuating potential of clumpy collapses inhibits disk formation and has been shown to be an effective formation mechanism for creating elliptical galaxies (Lake & Carlberg 1988; Katz & Gunn 1991; Steinmetz & Muller 1995). Figure 3 shows the proto-galactic mass distribution at a redshift of 10, just a billion years after the big-bang. The smallest collapsed halos that we can resolve have a mass of $10^7 M_{\odot}$, not much larger than globular clusters. The problem of baryonic trapping by star formation in lumps arises before the first QSO’s could ionize the intergalactic material (however, see Haiman, Abel & Rees 1999). The second problem is that the lumps do not dissolve by $z = 1$ or even by the present day, as we have shown. Even if we make the most optimistic assumptions about the fate of gas, the movements of this small tracer component will not lead to the destruction of the dark matter substructure.

![Figure 3](image-url)

**Figure 3.** The distribution of mass at a redshift $z=10$ in a 6 comoving Mpc region that forms a galactic halo by the present day. The colours show the smoothed local density at the position of each particle plotted in the range $\delta_{\rho/\rho} = 10 - 10^6$. The smallest halos that we can resolve have circular velocities of 10 km s$^{-1}$; virialised halos appear as bright yellow/white blobs. The cooling time for primordial gas within these halos is extremely short and leads to the “over-cooling” problem: most of the baryons in the universe will be trapped within low mass halos leaving no gas left to form disks at late times.

The most obvious observational constraints are the existence of old thin disks (Wielen 1972) and cold stellar streams (Shang et al. 1998). Just as gravitational perturbations from encounters transform disk galaxies to spheroidals in clusters (Moore et al. 1996), the passage of these lumps will heat any disk within the halo. Stellar disks extend to $\sim 10\%$ of the virial radius of the dark matter halo although HI can be observed to much larger distances ($25\%$ of $r_{vir}$ for some LSB galaxies).

We find that the orbits of satellites within our simulated halos have a median apocentric to pericentric distance of 6:1, therefore over the past 10 billion years disks will suffer many thousands of impulsive shocks and resonant heating. The single accretion of a satellite as large as the Large Magellanic Cloud, has a devastating effect on the disk of the Milky Way (Toth & Ostriker 1992; Ibata et al. 1998, Weinberg 1998). While recent work has noted that disks embedded within live halos may precess in response to a single satellite and avoid strong vertical heating (Huang & Carlberg 1997; Velazquez & White 1998), there are far too many clumps in our simulations for this mechanism to be effective.

An estimate of the heating can be obtained using the impulse approximation. Each dark halo that passes nearby or through the disk, will increase the stellar velocities across a region comparable to the size of the perturber by an.
We measure $m$, $v$, $\delta v$ and $V$ for each clump that orbits through the stellar disk. Summing the $\delta v$'s in quadrature over 10 Gyrs, we find that the energy input from encounters is a significant fraction of the binding energy of the stellar disk $\sim M_b v_c^2$, where $M_b$ and $v_c$ are the disk mass and rotation velocity respectively. The heating is more than sufficient to explain the age-temperature relation for disk stars (Wielen 1974), although the validity of the impulse approximation needs to be examined using numerical simulations. We note that the existence of old thin disk components, or galaxies such as NGC 4244 that does not have a thick disk (Fry et al. 1999), presents a severe problem for hierarchical models.

Substructure can be probed by gravitational lensing even if stars are not visible in the potential wells (e.g. Hogan 1999). Multiply imaged quasars are particularly sensitive to the foreground mass distribution; the quadruple images QSO 1422+231 cannot be modeled with a single smooth potential (Mao & Schneider 1998) and requires distortions of $\approx 1\%$ of the critical surface density within the Einstein radius. Dark matter substructure located in projection near to the primary source would create such distortions. If we extrapolate our mass function to smaller masses, we expect $\approx 10^5$ clumps with $v_c/V_{200} > 0.01$ ($m_b \approx 10^6M_\odot$). This may cause many gravitationally lensed quasars to show signs of substructure within the lensing potentials.

Cold dark matter candidates, such as axions and neutralinos, can be detected directly in the laboratory. Many proposed and ongoing experiments will be highly sensitive to the phase space distribution of particles at our position within the galaxy, yet calculations of experimental rates still assume that CDM particles passing through minute detectors have a smooth phase space distribution. We have shown that CDM halos are far from smooth, furthermore, the particle velocities in a single resolution element have a discrete component that results from the coherent streams of particles tidally stripped from individual dark matter halos. We may also an expect enhanced gamma-ray flux from neutralino annihilation within substructure cores (Lake 1990, Bergstrom et al. 1998).

4. SUMMARY

In a hierarchical universe, galaxies are scaled versions of galaxy clusters, with similar numbers and properties of dark matter satellites orbiting within their virial radii. The amplitude and tilt of the power spectrum, or varying the cosmological parameters $\Omega$ and $\Lambda$ will have little effect on the abundance of substructure. These only slightly alter the merger history and formation timescales. Any difference in merger history will be less than what we have already explored by comparing the cluster to the galaxy. Furthermore, we have shown that the properties of the substructure do not change over a 4 Gyr period, therefore an earlier formation epoch will not change these results.

If we appeal to gas physics and feedback to hide 95% of the Milky Way’s satellites then we must answer the question why just 5% formed stars with relatively normal stellar populations and reasonably large baryon fractions. If this problem can be overcome, then the substructure has several observational signatures, namely disk heating, gravitational lensing and direct/indirect particle dark matter detection experiments. Unfortunately, the existence of old thin disks with no thick/halo components may force us to seek a mechanism to suppress small scale power e.g. free streaming by a neutrino of mass $\sim 1$ keV (Schaeffer & Silk 1988).

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