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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 the 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 virialized extent of the Milky Way's halo should contain about 500 satellites with circular velocities larger than the Draco and Ursa Minor systems, i.e., bound masses $\gtrsim 10^8\ M_\odot$ and tidally limited sizes $\gtrsim 1$ 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 have important implications for the existence of old thin disks, cold stellar streams, gravitational lensing, and indirect/direct detection experiments.

Subject headings: cosmology: observations — cosmology: theory — dark matter — galaxies: clusters: general — galaxies: formation

1. INTRODUCTION

The growth of structure in the universe by the 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 play only 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 it has been invoked to set the scale for survival versus disruption (Rees & Ostriker 1977; White & Rees 1978).

Comparing the predictions of this model with nonlinear structures, such as the internal properties of galaxy clusters, has proved to be difficult. Numerical simulations had ubiquitously failed to find surviving substructure or "halos orbiting within halos" (e.g., Katz & White 1993; Summers, Davis, & Evrard 1995). It was generally thought that the so-called "overmerging" problem could be overcome by the inclusion of a baryonic component to increase the potential depth of galactic halos.

Analytic work suggested that overmerging was due entirely to poor spatial and mass resolution (Moore, Katz, & Lake 1996a). This has been verified by higher resolution simulations of clusters in which galactic halos survive without any inclusion of gasdynamics (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). Overmerging on galactic scales is a necessary requirement, otherwise previous generations of the hierarchy would preclude the formation of disks. Observations suggest that overmerging has been nearly complete on galactic scales. The Milky Way contains just 11 satellites within its virial radius with $\sigma_{\rm satellite}/\sigma_{\rm halo} \gtrsim 0.07$, which is equivalent to $\sigma_{\rm satellite} = 10$ km s^{-1} (cf. Mateo 1998 and references within). The same velocity-dispersion ratio in a cluster corresponds to counting galaxies more massive than the Large Magellanic Clouds ($\sigma_{\rm LMC} \sim 50$ km s^{-1}); there are 500–1000 such systems in a rich cluster (Binggeli, Sandage, & Tammann 1985; Driver, Couch, & Phillipps 1999). The same discrepancy exists at higher masses. The Coma Cluster contains $\gtrsim 30$ galaxies brighter than the characteristic break in the luminosity function, $L_* \equiv \sigma > 200$ km s^{-1} (Lucey et al. 1991). By scaling this limit to a galaxy halo, we find just two satellites in the Milky Way or three near Andromeda.

Why should substructure be destroyed in galactic halos but not in clusters? Analytic calculations suggested that galaxies should contain more satellites than are observed (Kauffmann, White, & Guilderdoni 1993). The shape of the power spectrum varies over these scales in a way such that galaxies form several billions of years before the clusters, and as a result, 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 that have sufficient force and mass resolution to resolve satellite galaxies as small as Draco. This allows us to

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

make a comparative study with observations and simulations of larger mass halos.

2. SUBSTRUCTURE WITHIN GALAXIES AND CLUSTERS

We simulate the hierarchical formation of dark matter halos in the correct cosmological context using the 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 realized within the volume that collapses into this object with progressively lower resolution at increasing distances from the object. The simulation is then rerun to the present epoch with the higher mass and force resolution. We have applied this technique to several halos identified from a 10^6 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 here is one in which the universe is dominated by a critical density of cold dark matter, normalized to reproduce the local abundance of galaxy clusters.

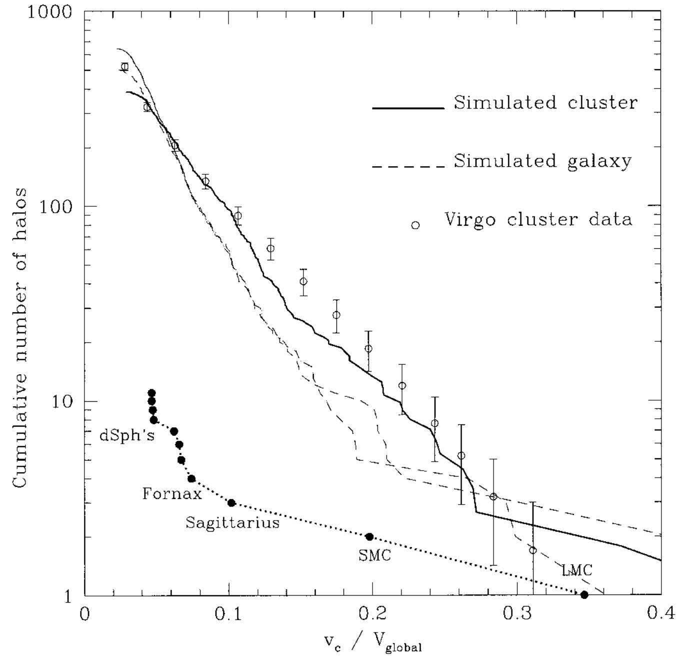

FIG. 2.—Abundance of cosmic substructure within the Milky Way, the Virgo Cluster, and our models of comparable masses. We plot the cumulative numbers of halos as a function of their circular velocity, $v_c = (Gm_b/r_b)^{1/2}$, where m_b is the bound mass within the bound radius r_b of the substructure, normalized to the circular velocity, $V_{\rm global}$, 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 are data for the Virgo 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.

The important numerical parameters to remember are that each halo contains more than one million particles within the final virial radius $r_{\rm vir}$ and that we use a force resolution that is ~0.1% of $r_{\rm vir}$. 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 of $z = 0$ 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 Gyr later than the galaxy halo. Both objects contain many dark matter substructure halos. We apply a group-finding algorithm to extract the subclumps from the simulation data, and we use the bound particles to measure their kinematical properties directly: mass, circular velocity, radii, and orbital parameters (cf. 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 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, while 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 consider it a remarkable success that this model reproduces both the shape and the amplitude of the galaxy mass function within a cluster.

In Figure 2, the cumulative distribution of the 11 observed satellites that lie within 300 kpc of the Milky Way is also plotted. Where necessary, we have converted one-dimensional velocity dispersions to circular velocities, assuming isotropic velocity distributions. The model overpredicts the total number of satellites that are larger than the dwarf spheroidals (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 $n(v/V_{\rm vir}) \propto (v/V_{\rm vir})^{-4}$, which is similar to that found by Klypin et al. (1999) for satellites in close proximity to galactic halos. The mass function within these systems can be approximated by a power law with $n(m/M_{\rm vir}) \propto (m/M_{\rm vir})^{-2}$. 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 against disruption by tidal forces (Moore et al. 1998).

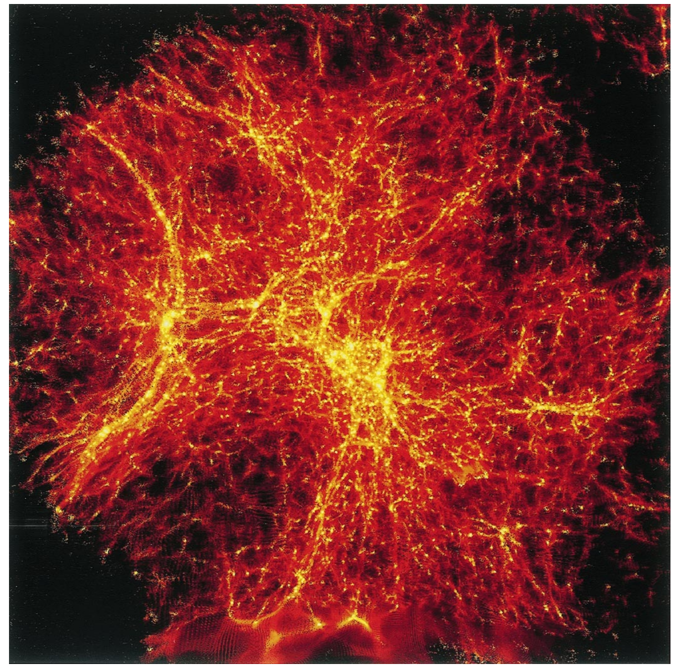

FIG. 3.—The distribution of mass at a redshift of $z = 10$ in a 6 comoving Mpc region that forms the present-day galactic halo. The colors show the smoothed local density at the position of each particle plotted in the range $\delta\rho/\rho = 10$–10^6. The smallest halos that we can resolve have circular velocities of 10 km s^{-1}; virialized halos appear as bright yellow/white blobs. The cooling time for primordial gas within these halos is extremely short and leads to the "overcooling" 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.

3. DISCUSSION

Either the hierarchical model is fundamentally wrong or the substructure lumps are present in the Galactic halo but contain too few baryons to be observed. The deficiency of satellites in galactic halos is similar to the 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 in order 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 by a struggle between gravity and winds. The strongest starbursts 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 during 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 QSOs 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.

The most obvious observational constraint is the existence of old thin disks (Wielen 1974) and cold stellar streams (Shang et al. 1998). Just as gravitational perturbations from encounters will transform disk galaxies into spheroidals in clusters (Moore et al. 1996b), the passage of these lumps will heat any disk within the halo. Stellar disks extend to ~10% of the virial radius of the dark matter halo, although H I can be observed at much larger distances (25% of $r_{\rm vir}$ for some low surface brightness 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 have suffered 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 & Razoumov 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 1999), 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 clump by an amount $\delta v \sim Gm_b/r_bV$, where V is the impact velocity. We measure m_b, r_b, and V for each clump that orbits through the stellar disk. Summing the δv's in quadrature over 10 Gyr, we find that the energy input from encounters is a significant fraction of the binding energy of the stellar disk, $\sim M_dv_c^2$, where M_d 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 do 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 of QSO 1422+231 cannot be modeled with a single, smooth potential (Mao & Schneider 1998) and require distortions of ≈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 $v_c/V_{200} > 0.01$ ($m_b \approx 10^6\ M_\odot$). This may cause many gravitationally lensed quasars to show signs of substructure within the lensing potentials.

Cold dark matter (CDM) 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 expect an enhanced gamma-ray flux from neutralino annihilation within substructure cores (Lake 1990a, 1990b; Bergstrom et al. 1999).

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 the varying of the cosmological parameters Ω and Λ, 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 with 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% of the satellites 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 for suppressing small-scale power (e.g., free streaming by a neutrino of mass ∼1 keV).

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