SQUELCHED GALAXIES AND DARK HALOS

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ABSTRACT

There is accumulating evidence that the faint end of the galaxy luminosity function might be very different in different locations. The luminosity function might be rising in rich clusters and flat in regions of low density. If galaxies form according to the model of hierarchical clustering, then there should be many small halos compared to the number of big halos. If this theory is valid, then there must be a mechanism that eliminates at least the visible component of galaxies in low-density regions. A plausible mechanism is photoionization of the intergalactic medium at a time before the epoch that most dwarf galaxies form in low-density regions but after the epoch of formation for similar systems that ultimately end up in rich clusters. The dynamical timescales are found to accommodate this hypothesis in a flat universe with $\Omega_m \approx 0.4$. If small halos exist but simply cannot be located because they have never become the sites of significant star formation, they still might have dynamical manifestations. These manifestations are hard to identify in normal groups of galaxies because small halos do not make a significant contribution to the global mass budget. It could be entertained, however, that there are clusters of halos where there are only small systems, clusters that are at the low-mass end of the hierarchical tree. There may be places where only a few small galaxies managed to form, enough for us to identify and use as test probes of the potential. It turns out that such environments might be common. Four probable groups of dwarfs are identified within 5 Mpc, and the assumption that they are gravitationally bound suggests $M/L_B \sim 300-1200 M_\odot/L_\odot$, a factor of 6 ± 2 times higher than typical values for groups with luminous galaxies.

Subject headings: dark matter — galaxies: formation — galaxies: luminosity function, mass function

1. EXPECTATIONS

According to the popular cold dark matter (CDM) hierarchical clustering model of galaxy formation, there should be numerous low-mass dark halos still around today. The approximation by Press & Schechter (1974) that initial density fluctuations would grow according to linear theory to a critical density and then collapse and virialize leads, with a CDM-like power spectrum, to a prediction of sharply increasing numbers of halos at smaller mass intervals. Cosmological simulations are now being realized with sufficient mass resolution to distinguish dwarf galaxies, and this modeling basically confirms expectations of the existence of low-mass halos (Klypin et al. 1999; Moore et al. 1999). Ninety percent of low-mass halos accreted into a cluster may be disrupted by tidal stripping or absorbed by dynamical friction, but the halo mass function is still anticipated to rise steeply toward lower masses (Bullock, Kravtsov, & Weinberg 2000).

Indeed, dwarf galaxies are found in abundance in some environments. In the past, most observational effort has gone into studies in rich clusters because the statistical contrast is highest against the background (Smith, Driver, & Phillipps 1997; Trentham 1998b; Phillipps et al. 1998; also the small but dense Fornax Cluster; Kambas et al. 2000). The general conclusion from these studies has been that, yes, there are substantial numbers of dwarfs of the spheroidal type. The high dwarf fraction reported in some instances may be in agreement with expectations of CDM hierarchical clustering theory.

There has been a suspicion, however, that there might not be the expected abundance of dwarfs in environments less extreme in density than the rich clusters. Klypin et al. (1999) and Moore et al. (1999) have pointed out the apparent absence of large numbers of dwarfs in the Local Group. It is to be appreciated that the task of identifying extreme dwarfs is not trivial. They are tiny and faint. At substantial distances their surface brightnesses are faint against the sky background, and close up they resolve into swarms of very faint stars. So, dwarfs were not being found in the expected numbers, but is this because of observational limitations?

Already, at relatively high intrinsic luminosities there is good evidence of variations of the galaxy luminosity function with environment. The luminosity function is steeper (larger dwarf/giant fraction) in denser groups characterized by thermal X-ray emission or high-velocity dispersions (Zabludoff & Mulchaey 2000; Christljen 2000). The trends are subtle in these studies because the faint-end cutoffs barely include what would normally be considered dwarf galaxies. For example, Zabludoff & Mulchaey (2000) go comparatively faint, to $M_R = -16.6 + 5 \log h_{75}$, where $h_{75} = H_0/75$.

2. FOUR ENVIRONMENTS

Motivated by the speculation that the occurrence of dwarfs might be correlated with local density, we made extensive observations in the nearest environment where the density is low (dynamical time is long) yet where there are enough galaxies for a meaningful statistical discussion. We studied the Ursa Major Cluster, a structure fortuitously at about the same distance as the Virgo Cluster that subtends a

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comparable amount of sky. The total light in bright galaxies in Ursa Major is about \( \frac{1}{4} \) that in Virgo, but dynamical evidence suggests that the mass in Ursa Major is down by a factor of 20 from that associated with Virgo (Tully & Shaya 1998). Roughly 16 deg\(^2\) of the Ursa Major Cluster were surveyed with deep CCD imaging with wide-field cameras on the Canada-France-Hawaii Telescope and in the 21 cm hydrogen line with the Very Large Array. Results of the two aspects of the survey are being reported, respectively, by Trentham, Tully, & Verheijen (2001) and Verheijen et al. (2000; M. Verheijen et al. 2002, in preparation). The optical survey provides information on dwarfs to a completeness limit of \( M_B = -10 \). The \( \text{H}\alpha \) survey confirms that there is no hidden component that is gas-rich.

In a separate study, Trentham & Hodgkin (2002) have searched for dwarfs in a 25 deg\(^2\) swath of the Virgo Cluster using images acquired as part of the 2.5 m Isaac Newton Telescope Wide Field Survey. Roughly 20% of the cluster is covered and provides information on the luminosity function down to a completeness limit \( M_B \sim -11 \). The results are consistent with what was found by Sandage, Binggeli, & Tammann (1985) but quite divergent from the situation suggested by Phillipps et al. (1998). These latter authors found a pronounced steepening of the luminosity function faintward of \( M_B = -15.5 \) (\( M_B \sim -14 \)), which Trentham & Hodgkin (2002) speculate is attributed to background contamination. In any event, as we will see further along, whether the moderately rising luminosity function of Sandage et al. (1985) and Trentham & Hodgkin (2002) is a correct description or the more extreme situation described by Phillipps et al. (1998) is correct, the faint end of the galaxy luminosity function is steeper in the Virgo Cluster than in the Ursa Major Cluster.

Two more extreme environments have reasonably well defined luminosity functions: the high-density Coma Cluster and the low-density Local Group. The Coma Cluster has been studied by Trentham (1998a). The data assembled for the Local Group is discussed by Trentham & Hodgkin. The \( B \)-band luminosity function data for all four environments discussed above are shown in Figure 1 (extracted from Trentham & Hodgkin 2002).

The main qualitative point to be drawn from this figure is that the slopes of the four luminosity functions are not the same. There is a steepening correlated with the richness of the cluster, progressing from the Local Group, through the Ursa Major Cluster and the Virgo Cluster, to the Coma Cluster. The observational situation is still not fully clear, but the case is becoming strong that there are environmental differences in the opposite sense of the expected dark matter halo mass trends that are discussed in the next section.

### 3. SQUELCHED GALAXIES

According to hierarchical clustering theory, as time goes on small halos merge or are disrupted. Still, the theory anticipates that there should be numerous dwarf galaxies relative to giant galaxies, perhaps in accordance with the observed situation in rich clusters. The ratio of dwarfs to giants is expected to depend on the pace of the merging process governed by the local density. At first thought, it would seem that the rich clusters are more hostile and the low-density regions more benign for the survival of small galaxies. In very low density groups dynamical collapse times can be of order of the age of the universe. The merging process is not so far advanced, and dynamical friction and tidal stripping have reduced consequences. In \( N \)-body simulations, Sigad et al. (2000) have found a greater survival of small halos compared to large ones in more isolated environments. Thus, the general expectation would be that there are more dwarfs per giant in low-density, less evolved regions, precisely the opposite of what is indicated in Figure 1. Conceivably, galaxy harassment of some sort could transform giant galaxies into dwarfs in clusters (Moore, Lake, & Katz 1998). It is in clusters, however, where there is better agreement between observations and theoretical expectations. We are confronted with the problem of the absence of dwarfs in low-density regions. If dwarfs can be formed from harassment in clusters, it would only extend the disparity with the predictions of CDM theory to clusters (the expected large numbers of primordial dwarfs would not be found anywhere). At face value, we need to call upon a mechanism that \textit{allows} small galaxies to form in rich clusters but \textit{thwarts} small-galaxy formation in places of low density.

A plausible mechanism is photoionization of the intergalactic medium before the epoch of galaxy formation. Efsta-thiou (1992) discussed the inhibiting effect on the formation of dwarfs due to the suppression of cooling of a primordial plasma of hydrogen and helium. Thoul & Weinberg (1996) took the discussion further with recourse to high-resolution hydrodynamic simulations. These authors argue that gas heating before collapse is more important than inhibition of
line cooling. The suppression of galaxy formation occurs below a virial velocity threshold. The UV background heats the precollapse gas to roughly 25,000 K. This temperature is much less than that associated with the virial energy of a large galaxy, hence it has negligible effect on the collapse of baryons into a massive potential well. For a sufficiently small galaxy, however, this heating is comparable with, or can dominate, the gravitational energy. Thoul & Weinberg and also Gnedin (2000) find that there is essentially total suppression of baryon collapse for systems with circular velocities $V_{\text{circ}} < 30$ km s$^{-1}$ and, by contrast, little effect on galaxy formation for systems with $V_{\text{circ}} > 75$ km s$^{-1}$. It follows that luminosity functions would be little affected above $M_B \sim -18 + 5 \log h_{75}$ but strongly attenuated below $M_B \sim -15 + 5 \log h_{75}$.

The suppression of baryon collapse would only apply to galaxy formation that occurs after reheating of the intergalactic medium. The collapse timescale (Gunn & Gott 1972)

$$t_{\text{col}} = 1.4 \times 10^{10} (R_{\text{vir}}^3 / M_{14})^{1/2} h_{75}^{-1} \text{ yr},$$

where $R_{\text{vir}}$ is the virial radius in Mpc and $M_{14}$ is the virial mass in units of $10^{14} M_\odot$. Values for $R_{\text{vir}}$ and $M_{14}$ can be extracted from Tully (1987) for the Virgo and Ursa Major clusters ($R_{\text{Vir}} = 0.79$ and 0.98 Mpc, respectively; $M_{14} = 8.9$ and 0.5, respectively). Hence, rough dynamical collapse times for these clusters are $t_{\text{col}}^{\text{Virgo}} \sim 3.3$ Gyr and $t_{\text{col}}^{\text{UMa}} \sim 19$ Gyr. The dense, elliptical-dominated Virgo Cluster formed a core long ago, and the loose, spiral-dominated Ursa Major Cluster is still in the process of collapsing. Of course, galaxies continue to fall in and enlarge the Virgo Cluster to this day, and, on the other hand, substructure in Ursa Major would have shorter dynamical collapse times than the entire entity. Smaller mass scales collapse before larger mass scales. Dwarfs must form before their host cluster forms. The timing of halo collapse and mergers as a function of environment will be considered in the next section. To conclude this section, we review the evidence on the timing of reionization of the intergalactic medium by the UV radiation of active galactic nuclei (AGNs) or hot stars.

Observations constrain the epoch of reionization to $z \gtrsim 6$ (Fan et al. 2000; Becker et al. 2001), which can be understood on theoretical grounds (Gnedin & Ostriker 1997). In Figure 2, we see the relationship between redshift and the age of the universe for a wide range of flat-world models. If baryon collapse into small galaxies can occur only before reionization, then Figure 2 tells us crudely that if the epoch of reionization is as late as $z_{\text{ion}} \sim 6$, then dwarfs with $t_{\text{col}} \sim 1$ Gyr could form in a universe with matter density $\Omega_m \sim 0.2$ and vacuum energy density $\Omega_{\Lambda} \sim 0.8$.

4. SIMULATIONS

We use semianalytic models of galaxy formation based on the code developed by Somerville (1997) and described in detail by Somerville & Primack (1999) and Somerville, Primack, & Faber (2001). The formation history of collapsed dark matter halos and their substructure is described via Monte Carlo sampling based on the extended Press-Schechter formalism (Somerville & Kolatt 1999). Radiative cooling by atomic hydrogen, formation of stars, and feedback due to supernovae winds is modeled with simple empirical recipes described in the references above. In this paper, we also include a recipe to suppress gas accretion because of heating by an external photoionizing background, a feature not previously included in a full semianalytic model. We describe this new ingredient briefly below. The concepts are discussed further by Somerville (2001).

A recipe for suppression of gas collapse is adopted from Gnedin (2000) and produces results consistent with Thoul & Weinberg (1996). Reionization is assumed to take place instantaneously at a redshift $z_{\text{ion}}$. In halos of virial mass $M_{\text{vir}}$ that collapse before reionization, the mass of participating gas $M_g$ available to ultimately make stars is

$$M_g = f_b M_{\text{vir}},$$

where $f_b = \Omega_b / \Omega_m$ is the universal baryon fraction. In halos collapsing after reionization, there is suppression of the participation of gas in the collapse:

$$M_g = \frac{f_b M_{\text{vir}}}{(1 + 0.26 M_{50} / M_{\text{vir}})},$$

where halos with $M_{50}$ retain 50% of their baryon mass. Acceptable results are found if $M_{50}(z_c)$ is the mass associated with a halo with virial velocity $50$ km s$^{-1}$ at a collapse epoch $z_c$. Since halos collapsing later have lower density, $M_{50}(z_c)$ increases as $z_c$ decreases. It follows from this recipe that after reionization, gas collapse is suppressed completely in halos with $V_{\text{vir}} < 30$ km s$^{-1}$ and is almost unaffected in halos with $V_{\text{vir}} > 75$ km s$^{-1}$. When this new ingredient is included, the luminosity function of satellite galaxies in the Local Group predicted by our model is in good agreement with observations (Somerville 2001).
When do dwarf galaxies form in environments of different total mass? This question can be addressed by following back the merger trees in semianalytic simulations. As a matter of definition, it is taken that a subhalo within a parent halo forms at the redshift $z_f$ when the largest progenitor has a mass of half the final subhalo mass. This discussion considers only final subhalos with virial velocities in the range $17 < V_{\text{cir}} < 50 \, \text{km s}^{-1}$, the range strongly susceptible to squelching of star formation by reionization.

The merger trees can be traced back in virialized parent halos with a range of masses, $M_{\text{H}}$. In Figure 3, we see the distribution of formation redshifts for squelchable dwarf halos embedded in parent halos with masses $10^{11} - 10^{14} \, M_\odot$. The solid histograms are based on the “progenitor with half the final mass” definition of subhalo formation, while the dotted histograms represent the formation epoch of the “oldest progenitor” (the redshift at which the first progenitor has gas at $10^4 \, \text{K}$ that can cool). The quantity $dP/dz_f$ is the fraction of dwarf halos with formation redshifts in the interval $z, z + dz_f$.

The definition of the formation epoch in terms of the development of a progenitor with $50\%$ of the final mass is arbitrary. Figure 4 shows the cumulative distribution of the fraction of the final subhalo mass that is in a single progenitor at $z = 8$; i.e., if we define $f \equiv M(z = 8)/M_0$, where $M_0$ is the final mass of the dwarf subhalo, then the plot shows the fraction of objects whose largest progenitors have fractional mass greater than the quantity plotted on the $x$-axis. Thus, if we assume a simple picture in which a subhalo survives squelching if it has some fraction of its final mass in place at reionization (as in the model of Bullock et al. 2001), then we can read the fraction of surviving galaxies off of the plot for any assumed value of the critical fraction $f$ and for various parent halo masses. We see again that a much larger fraction of dwarfs will survive squelching in high-mass halos. The plot assumes $z_{\text{ion}} = 8$, but the results are insensitive to the precise epoch of reionization.

The quantity $dP/dz_f$ shown in Figure 3 can be integrated to determine the fraction of dwarf halos that formed before the epoch of reionization $z_{\text{ion}}$ in any specified parent halo.

**Fig. 3.—**Distribution of formation redshifts for dwarf halos ($17 < V_{\text{cir}} < 50 \, \text{km s}^{-1}$) within virialized parent halos ranging from $10^{11}$ to $10^{14} \, M_\odot$. Solid histograms: Formation epoch defined by development of a progenitor with half the final dwarf subhalo mass. Dotted histograms: Formation epoch of first progenitor to cool. The vertical tick marks in the lower left corners of each panel indicate the average formation redshift of the parent halos (half the final mass in place). More massive halos formed later but, within them, small halos tended to form earlier in environments that became more massive clusters.
Integrally, it is plausible that the larger dwarf fraction in the Virgo Cluster \((8 \times 10^{14} \, M_\odot)\) comes about because many dwarf halos were in place in the proto-Virgo region before reionization, while the smaller dwarf fraction in the Ursa Major Cluster \((4 \times 10^{13} \, M_\odot, \text{or smaller, since UMa is probably not virialized at this mass})\) is a consequence of the fact that few dwarf halos were in place before reionization. Interestingly, this squelching mechanism produces a pronounced differential with environment only in a universe with relatively low matter density, say, \(\Omega_m < 0.4, \Omega_\Lambda > 0.6\). In a universe with \(\Omega_m = 1\), structure forms at low redshift: \(t_{\text{col}} \sim 1 \, \text{Gyr}\) corresponds to \(z \sim 3\).

It would follow that if a range of cluster environments is explored, then there should be a rollover: denser clusters with short dynamical times will have a large dwarf/giant fraction, and less dense clusters with long dynamical times will have a small dwarf/giant fraction. The collapse timescale associated with a break-point density would reflect the time of reionization of the universe.

In addition to counts of numbers of dwarfs, it is known that the fractional representation of different types of dwarfs depends on environment (Binggeli, Sandage, & Tammann 1988). There are more gas-depleted types in denser clusters and more irregulars with ongoing star formation in low-density regions. If the halos of all these systems were in place and gas had accumulated before the time of reionization (our hypothesis), then we would follow that there would be very old stars in these systems, whatever their type. In fact, old stars are found in all galaxies that have been observed appropriately. Evidently, the pace of the transition of cold gas into stars is highly variable from dwarf to dwarf. Even among spheroidals that have no gas or recent star formation, there is evidence in well-studied nearby cases that star formation went on in spurts over extended intervals (Mateo 1998).

5. A SEARCH FOR DARK HALOS

If the preceding ideas have any merit, then it follows that there would be many low-mass halos that are not identified because they contain few stars or neutral gas. In groups with luminous galaxies, the fractional mass representation of unlit halos would be expected to be small, and such halos would have little dynamical consequence. The overall ratio of mass to light would be reflective of the properties of the dominant galaxies and their halos. In the very low mass regime, maybe there are collapsed halos where no stars were born, but we cannot find those places. In between, following from the hypothesis that there are squelched dark halos, there could be groups where some halos have birthed stars but where \(M/L\) is large. Maybe there are groups with only low-luminosity galaxies where the contribution to the mass inventory from dark halos might be significant.

In a group catalog that includes galaxies of very low luminosities (Tully 1987, 1988), it already appeared that there might be bound systems of dwarf galaxies. When these group candidates were found, it was appreciated that if they are bound, then they must have large \(M/L_B\) values. No big deal was made of these group candidates because the statistical status of the sample was poor. If CDM hierarchical clustering theory is valid, however, then the deficiency of visible dwarfs requires the existence of invisible dwarfs. The existence of groups of dwarfs with high \(M/L\) would be a reasonable expectation at the transition from the regime of luminous groups to the regime of totally invisible groups. Hence, the candidate groups of dwarf galaxies (called “associations” in 1987) deserve renewed attention. With the passage of a decade, there have been new dwarf identifications. In fact, the amount of new information is remarkably limited, evidence of an indirect nature that dwarf halos with stars are not numerous. For our purposes, the most important new surveys for dwarfs are by Karachentseva & Karachentsev (1998), with follow-up \(H\) observations by Huchtmeier et al. (2000), and the study of the Sculptor and Centaurus regions by Coté et al. (1997).

Our new inventory of possible dwarf groups extends to \(~5\,\text{Mpc}\). Beyond this distance, extreme dwarf galaxies tend to be too faint and deficient in \(H\) to be reliably identified. The search is restricted to relatively high Galactic latitudes, since dwarfs are very difficult to find in the Galactic plane. In this modest volume we find four groups of three to six dwarf galaxies each. One of these groups is, in fact, at the rather low latitude \(b \sim 18^\circ\) in a region of low obscuration near the Galactic anticenter. The brightest galaxies in these groups have \(M_B \sim -16\), with \(V_{\text{circ}} \sim 45\,\text{km}\,\text{s}^{-1}\). The global...
properties of these small groups are summarized in Table 1. The numeric names of the groups are drawn from Tully (1988).

Before focusing on the properties of these four small groups, it is worth a reflection on what else is going on within this 5 Mpc region. Beyond the Local Group, there are four other groups at high Galactic latitude with big galaxies: the Canes Venatici (14–7), M81 (14–10), Sculptor (14–13), and Foreground Sculptor (14+13) groups (dominant galaxies: NGC 4736, NGC 3031, NGC 253, and NGC 55, respectively). Information is provided in Table 1 on these groups and also the group around M31 within the historical Local Group. The Centaurus (14–15) group flirts with the zone of obscuration at $b > 20^\circ$. There are three more groups at $|b| < 15^\circ$: Maffei–IC 342 (14–11), Circinus (14+20), and a newly revealed group around NGC 6946. At $|b| > 30^\circ$, 80% of galaxies suspected to be within 5 Mpc are in or closely associated with the groups identified above and in Table 1. Otherwise, there are only a couple of pairs and a dozen other galaxies with $M_B < -14$ not associated with groups but within the filaments called 14 and 17 (Tully 1988). We should have a complete census of all H$\alpha$–rich systems at $|b| > 20^\circ$, $M_B < -14$, and $d < 5$ Mpc.

The four dwarf groups identified in Table 1 are clearly distinguished. Given the small dimensions and velocity dispersions, the dwarf groups represent a highly significant correlation enhancement over an unclustered distribution. The galaxy number densities within the rms separation shells containing 68% of group members ($\langle R_{3D} \rangle$ in Table 1) are 3–80 galaxies Mpc$^{-3}$ for the four groups of dwarfs. The average number density in the volume within 5 Mpc but excluding the groups in Table 1 is 0.1 galaxies Mpc$^{-3}$.

The number of high-latitude dwarf groups is comparable to the number of high-latitude groups with giant galaxies, although the number of members per group is fewer. The dimension, velocity dispersion, light, and inferred mass properties of the dwarf groups can be compared with the properties of more familiar groups containing large galaxies (Tully 1987). In the summary provided in Table 1, projected radii ($R_p$) are the mean projected separations from the geometric centers of the identified members with no weighting. The $\langle R_{3D} \rangle$ are the equivalent three-dimensional radii, directly measured in the cases of the groups including NGC 3109 and NGC 224 (M31), but derived only statistically from $\langle 4/\pi \rangle \langle R_p \rangle$ for the cases in brackets. Velocity dispersions $\sigma_V$ are rms differences in radial motions from the

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**Fig. 5.** Fraction of dwarf halos formed before reionization in parent halos ranging in mass from $M_H = 10^{11}$ to $10^{14} \ M_\odot$. Solid curves: Galaxy formation epoch defined by acquisition of half the final mass. Dotted curves: Epoch of oldest progenitor.
The group including NGC 3109 is the nearest neighboring group to the Local Group. It is so near that it has sometimes been considered as part of the Local Group, but galactocentric velocities are all positive and the dispersion in velocities is tiny. Good distances, accurate to ~10%, are available for five of six prospective members from observations of either Cepheids or the luminosities of stars at the tip of the red giant branch. The remarkably similar distances place these galaxies together and substantially beyond the Local Group (van den Bergh 1999). The group has dimensions similar to groups with luminous galaxies (Tully 1987), and the number density contrast of a factor of 30 over an average local volume of space makes it likely that these galaxies are mutually bound. 

Distances to the other dwarf groups are considerably less certain. Nevertheless, the basic results seem well established. Group dimensions are similar to those of more familiar spiral groups. Velocity dispersions are very low, hence inferred masses are low. Since these are low-luminosity groups, however, \( M/L_B \) ratios are large. By comparison, more prominent groups have \( M/L_B = 94 L_\odot/L_\odot \pm \alpha \) a factor of 2 (Tully 1987; same distance and luminosity scales). The statistics are still slim, but the groups of dwarf galaxies seem to have \( M/L_B \) values a factor of 6 ± 2 times higher. Mass uncertainties are large, dominated by two factors. There are substantial random uncertainties in velocity dispersions, since sampling numbers are small and only line-of-sight components are observed. Moreover, there is ample room for systematic errors, since these dwarf groups are unlikely to be relaxed. An envelope to random uncertainties is provided by the factor of 2 scatter in the Tully (1987) groups with five or more members (this factor of 2 includes both measurement and intrinsic variances). The random uncertainty grows to a factor of 3 if only four members are known. As for systematic error, a crude estimate of a factor of 2 is pro-

\[
M = \frac{f_{pm}}{G(N - \alpha)} \sum_{i=1}^{N} R_p, \Delta V_i^2, \tag{4}
\]

where \( f_{pm} = 20/\pi \) is found by Tully (1987) to be statistically compatible with masses derived using the virial theorem (becomes \( f_{pm} = 5 \) and \( R_p \) becomes \( R_{3D} \) in the cases of the NGC 3109 and NGC 224 groups where three-dimensional positions are available), \( N \) is the number of group members, and \( \alpha = 1.5 \), following Heisler et al. The projected mass estimator and the mean projected radius from the group centroid, \( R_p \), are more stable than the virial mass estimator and virial or harmonic radius in cases where there are close projections. We make the underlying assumption that the galaxies are only test particles in the gravitational potential well, so luminosity weighting is inappropriate and there may not be any galaxy at the actual minimum of the potential. The groups are expected to be bound but not virialized, so mass estimates in these nonequilibrium conditions are uncertain. The lower mass limit that follows from the assumption that the group is bound is half the mass given by the virial estimate.
luminosities from the modeling as a function of halo mass for two cases: with no squelching (dashed line) and with squelching due to reionization at $z_{\text{ion}} = 10$ (solid line). The results of squelched models are similar for $z_{\text{ion}} = 6$–100. Without squelching, the ratio of light to mass is only a weak function of mass above $M_{\text{vir}} \sim 10^{10} M_\odot$, rising slightly higher at intermediate masses. The turnover below $M_{\text{vir}} \sim 10^{10} M_\odot$ is mainly due to supernova feedback. Below $M_{\text{vir}} \sim 10^{9} M_\odot$, there is a further cutoff because gas is not cooled by atomic processes. Squelching introduces a strong cutoff beginning at masses around $10^{11} M_\odot$, about an order of magnitude above the supernova feedback regime.

There is an important systematic that causes a displacement of the solid curve with respect to the observed data in Figure 6. The modeling pertains to virialized halos, but the dwarf groups are most unlikely to be virialized. The process of clustering in the dwarf groups is less far along than would be the case with virialized groups of the same mass. One can suppose that the dwarf groups might be composed of virialized subhalos with masses of $(1–3) \times 10^{10} M_\odot$ and scales of 45–60 kpc that are in the extended process of merging. Suppose we consider a group with mass $5 \times 10^{11} M_\odot$. The curve derived from the semianalytic models plotted in Figure 6 pertains to a virialized structure, and it is anticipated that $M/L$ will be modest in this circumstance. A bound structure made up of several $3 \times 10^{10} M_\odot$ virialized pieces, however, would be expected to have a much higher $M/L$. Suppression by reionization is greater at these very low subhalo masses than at the bound group mass scale. The superposition of the semianalytic modeling results on the observed data is not presented as a “good fit” but rather as an illustration of the form a cutoff could take. More attention needs to be given to the properties of bound but unvirialized structures in the simulations.

6. SUMMARY

1. The faint end of the luminosity function of galaxies might be rising in the dense environment of rich clusters but relatively flat in the low-density regions of groups. CDM theory predicts that the dark matter halo mass function is sharply rising at the low-mass end. It seems something is suppressing the visible manifestations of small galaxies in low-density environments.

2. Reionization of the universe at $z_{\text{ion}} > 6$ could inhibit the collapse of gas in low-mass potential wells for late-forming galaxies. Dynamical collapse times inferred from the observed densities of clusters are consistent with the picture that relatively more dwarf halos formed before reionization in high-density regions and relatively more formed after reionization in low-density regions, but only if structure is forming at high redshift, i.e., $\Omega_m \lesssim 0.4$ in a flat universe.

3. Using semianalytic models with a recipe for suppression of gas collapse into low-mass halos after reionization, within a $\Lambda$CDM cosmology, it is shown that more dwarf halos formed earlier in regions that ultimately become massive clusters. This statement refers to dwarf halos that avoid disruption or absorption and survive until today; many more halos formed early and are now lost. Qualitatively, the models anticipate that more dwarf halos were in place before reionization in protocluster environments, and compared with moderate density regions, the ratio of dwarf to
giant galaxies should be larger. This fundamental expectation appears to be observed.

4. Four small groups that contain only dwarf galaxies are found within 5 Mpc, comparable to the number of groups that contain large galaxies. Dynamical evidence is found for a lot of dark matter in these groups, with $M/L_B = 300-1200 M_\odot/L_\odot$, a factor of 6 ± 2 times higher than in groups with big galaxies. It is suggested that low-mass halos that never hosted significant star formation make up a significant fraction of the group mass in these places.

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