COLD DARK MATTER’S SMALL-SCALE CRISIS GROWS UP

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Received 2003 September 25; accepted 2004 May 25

ABSTRACT

The cold dark matter (CDM) theory predicts a wealth of substructure within dark halos. These predictions match observations of galaxy clusters like the nearby Virgo Cluster. However, CDM has a “small-scale crisis”: galaxies dominate the halo with little substructure, even though the model predicts that galaxies should be scaled versions of galaxy clusters, with abundant substructure. Compared to CDM predictions, the Milky Way and Andromeda are “missing” objects with velocity dispersions of \( \sigma \geq 10 \text{ km s}^{-1} \). The energy scale of these missing satellites is low enough that stellar winds and supernovae might remove gas and suppress the formation of their luminous stellar components. Here we show that the small-scale crisis persists in fossil groups that have masses of up to 40% of the nearby Virgo Cluster of galaxies. Fossil groups are missing satellites with luminosities that occur at the predicted frequency in the Virgo Cluster. Moreover, the “missing galaxies” in fossil groups are nearly as luminous as the Milky Way, with a velocity dispersion of \( \sigma \leq 150 \text{ km s}^{-1} \).

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

1. INTRODUCTION

The formation of structure in the universe by hierarchical clustering is an elegant and well-defined theory that explains observations of the universe on large scales (Blumenthal et al. 1984). In early simulations, it seemed that merging was too efficient to be consistent with the observed hierarchy of structures (White & Rees 1978). This “overmerging” problem was reproduced in simulations for several years (White et al. 1987; Frenk et al. 1988). While overmerging was a virtue on the scale of individual galaxies, it was a problem for rich clusters of galaxies. Solutions focused on the role of gas dynamics in making lumps within rich clusters of galaxies (Katz & White 1993). Eventually, Moore et al. (1996) showed that numerical heating dominated over physical mechanisms unless simulations had nearly \( 10^6 \) particles within the virial radius of a cluster. Simulations with this resolution reversed the picture, overmerging disappeared, and halos the size of the Milky Way were predicted to have nearly the same scaled distribution of substructure as the Virgo Cluster (Moore et al. 1999, hereafter M99; Klypin et al. 1999).

This strong prediction can be tested observationally. A Milky Way sized halo should have \( \sim 500 \) satellites within 500 kpc with circular velocities greater than 5% of the parent halo’s velocity, i.e., \( V_{\text{cir}}/V_{\text{parent}} > 0.05 \), in contrast to a scant 11 that are observed (Klypin et al. 1999; M99).

It has been suggested that the stellar components of the Milky Way’s satellites might have accumulated in the core regions of their dark halos, where the characteristic velocities \( \sigma \) are smaller than the asymptotic value of \( V_{\text{cir}} \). The observed velocities of the Milky Way’s satellites would be remapped to much higher peak values than expected, shifting the objects plotted in the left panel of Figure 1 to the right until they matched the theoretical prediction (Hayashi et al. 2003). There are still many satellites missing at lower peak velocities compared to CDM predictions, but these are declared to have gone dark as a result of the ejection of gas from systems with low escape velocities of only 20–60 km s\(^{-1}\). These objects are also deficient in the field (e.g., Kauffmann et al. 1993) where the same processes could keep them from being observed.

Is this the solution to the overmerging crisis? The ROSAT X-ray satellite discovered a new class of objects: fossil groups (Ponman et al. 1994). RX J1340.6+4018 at redshift 0.171 is the archetype, with a bright isolated elliptical galaxy, \( M_R = -22.7 \), surrounded by dark matter and a hot gaseous halo. The spatial extent of the X-ray emission, \( \sim 500 \) kpc; the total mass, \( \sim 6 \times 10^{13} M_\odot \); and the mass of the hot gas correspond to a galaxy cluster \( \sim 40\% \) as massive as Virgo, and the optical luminosity of the central galaxy is comparable to that of cluster cD galaxies (Jones et al. 2000, hereafter JPF00). Five additional fossil groups have been confirmed spectroscopically. For one of them, RX J1416.4, the X-ray temperature is estimated to be \( \sim 1.5 \) keV (Jones et al. 2003). Fossil groups are not rare. Their number density is \( \sim 2.4 \times 10^{-7} \frac{M_\odot}{h_7^3 \text{ Mpc}^{-3}} \) if we use the definition that they have a dominating giant elliptical galaxy with the next brightest object being 2 mag fainter, embedded in an X-ray halo with a luminosity 10%–60% of the Virgo Cluster (Vikhlinin et al. 1999; Jones et al. 2003). They comprise \( \sim 20\% \) of all clusters and groups with an X-ray luminosity larger than \( 2.5 \times 10^{42} \text{ ergs s}^{-1} \) and host nearly all field galaxies brighter than \( M_R = -22.5 \) (Vikhlinin et al. 1999). Their total mass density is comparable to massive galaxy clusters. Their high mass-to-light ratio, \( M/L_R \sim 300 \), is comparable to that of...
Virgo. The luminosity-temperature relations are also similar (Jones et al. 2003).

We define “overmerged” systems as objects dominated by a single central object with weak substructure, the Milky Way being a local prototype. In contrast, “clusters of galaxies” have abundant substructure and a central galaxy with a velocity dispersion that is considerably less than that of the overall dark halo, the local prototype being the Virgo Cluster. In this paper, we examine overmerging in systems with masses intermediate between those of the Milky Way and the Virgo Cluster.

2. THE CUMULATIVE SUBSTRUCTURE FUNCTION IN FOSSIL GROUPS

We compare the cosmological model predictions (De Lucia et al. 2004) to the substructure function of RX J1340.6+4018, the Virgo and Coma clusters of galaxies, Hickson compact groups (HCGs; Hickson 1982), and the Local Group. In Figure 1, the cumulative substructure function is the number of objects with velocities greater than a fraction of the parent halo’s velocity. The right panel shows a sample of five loose groups from Zabludoff & Mulchaey (2000) and the function derived from the LF of 39 HCGs (Hunsberger et al. 1998) compared to CDM predictions (dashed line).

The cumulative distribution of satellites in the Milky Way’s halo and Andromeda’s halo are also plotted. Here the measured one-dimensional velocity dispersions of satellites (Mateo 1998) are converted to circular velocities assuming an isotropic velocity dispersion (M99).

We would like to have a sample of LFs for objects with masses that fall between those of the Local Group and the Virgo Cluster. There are only a few LFs known in this range, most of them from studies of HCGs. Hunsberger et al. (1998) constructed an LF from 39 compact groups. To convert this to the substructure function in Figure 1 (right panel), we adopt \( \sigma \sim 370 \text{ km s}^{-1} \) for the typical velocity of the parent’s halo and use the Tully-Fisher relation that Mendes de Oliveira et al. (2003) have shown applies to galaxies in HCGs.

In the right panel of Figure 1, we show a composite substructure function for the five loose groups in Zabludoff & Mulchaey (2000). These look very different from the other substructure functions, appearing to be shifted strongly to the right compared to the composite for the 39 HCGs. While these objects could be very different, loose groups are likely to have even more contamination than typical HCGs (Hernquist et al. 1995), Zabludoff & Mulchaey (2000) point to the Local Group as an archetype of loose groups. While the Local Group is certainly a physical association, it is not bound and virialized. If we treated it as a group, the Milky Way would appear as the second-brightest member, and the rest of the points would move upward by a factor of 2. This would indeed be an archetypal substructure function for a loose group. If, instead, we waited for the virialization of the group and the merger of M31 and the Milky Way, we would see something extremely similar to the substructure function of the individual virialized systems. While the first few points of the combined substructure function of the 39 HCGs place them high on the predicted substructure function (Fig. 1, dashed line), the LFs quickly flatten and show a deficit of structure at the faint end (right panel). The combined substructure function of the five loose groups from Zabludoff & Mulchaey (2000) shows behavior that is intermediate between the HCGs and the brighter clusters.

Zabludoff & Mulchaey (1998b) find that their two groups with the greatest number of members (HCG 62 and NGC 741) can be broken into two distinct subgroups. They suspect that the fraction with such structure is much higher than 40%, since their statistic is less sensitive for the groups with fewer members and requires an angular offset of the centroids of the subclumps.

In the left panel of Figure 1, the similarity of the substructure function in RX J1340.6+4018 to the Milky Way and Andromeda is striking. It shows that fossil groups are also overmerged objects. However, for galaxies of any given \( V_{\text{cir}} \) that are missing in the fossil group, galaxies with the same \( V_{\text{cir}} \) appear with the predicted frequency in Virgo and are observed in the field as well. The Virgo Cluster contains six \( L^* \) galaxies (Binggeli et al. 1985), with \( L^* \) being a characteristic luminosity in the LF, roughly the luminosity of the Milky Way. Fossil groups show one or no \( L^* \) galaxies (Mulchaey & Zabludoff 1999; Jones et al. 2003), while the CDM substructure function predicts a few in each group. The likelihood that the substructure in fossil groups and in the Virgo Cluster is drawn from the same, universal cosmological distribution function is negligibly small, especially at the low-mass end.

3. THE TRANSITION FROM OVERMERGING TO GALAXY CLUSTERS

Where does the transition from overmerged systems to galaxy clusters with substantial substructure occur? Is the
transition from overmerging to clusters smooth, abrupt, or merely ill-determined with a scattering of points?

Studies of HCGs, loose groups (Zabludoff & Mulchaey 1998a, 1998b), the Two-Degree Field Galaxy Redshift Survey (2dFGRS; Colless et al. 2001), and the Sloan Digital Sky Survey (SDSS; York et al. 2000) are sources for catalogs of groups and clusters. Balogh et al. (2004) analyzed both surveys to look at “galaxy ecology,” or star formation as a function of environment. Desai et al. (2004) fitted some circular velocity functions to a sample from the SDSS and compared this to the large simulation by Reed et al. (2003). The critical range of group velocity dispersions is 250–400 km s\(^{-1}\), as this is where one would expect to see the transition from overmerging on the scale of galaxies to the abundant substructure in clusters. In this range, there are 39 objects in the HCG sample of Hunsberger et al. (1998), 5 loose groups in the sample of Zabludoff & Mulchaey (1998a), 9 SDSS groups from Desai et al. (2004), and roughly 40 groups from the 2dFGRS (Balogh et al. 2004). Only the HCGs and the loose groups have LFs that are deep enough to be used in the bottom panel of Figure 2. There are a few other sources with not quite enough information to be used. For example, the LFs observed by Muriel et al. (1998) show a number of groups with LFs that are similar to the HCG sample of Hunsberger et al. (1998), but the typical velocity dispersions for the groups are unknown.

We plot the number of galaxies brighter than \( M_B < -19 \) versus velocity dispersion in the top panel of Figure 2 using the data from Balogh et al. (2004) and Desai et al. (2004). As expected, the number of galaxies increases with the velocity dispersion of the group. We added a line that shows what one would observe if the substructure function of Virgo were universal. At low dispersion, it appears that objects have more substructure than a scaling of Virgo. This is because of the criteria that there must be 10 members to be included as a group in the samples. With the cut of \( M_B < -19 \), the Milky Way would still be consistent with a scaled Virgo substructure function. At the high velocity dispersion end, there is less substructure than the scaled Virgo substructure function predicts. This is consistent with previous studies in which the luminosity function within large clusters was relatively constant rather than scaling with cluster size (De Propris et al. 2003). There is not a large sample of such clusters in CDM simulations. There are a few high-resolution runs of individual clusters (Borgani et al. 2002), and the high-resolution run of Reed et al. (2003) simulated a volume of 100 Mpc a side, which is not large enough for a good sample of large clusters.

There are fewer mass functions that reach \( V_{\text{circ}}/V_{\text{parent}} > 0.05 \), and these have been collected in the bottom panel of Figure 2. This sample includes all the systems shown in Figure 1 and adds the Fornax Cluster. Fornax has a velocity dispersion of \( \sigma \sim 374 \text{ km s}^{-1} \), comparable to RX J1340.6+4018, but little diffuse X-ray emission (e.g., Horner et al. 1999) and considerably more substructure (obtained from the LF of Ferguson & Sandage 1989), albeit less than a scaled version of Virgo would predict. For RX J1340.6+4018, integrating the luminosity function within the large error bars gives an upper limit of \(~30\) members with \( V_{\text{circ}}/V_{\text{parent}} > 0.05 \), but only 9 are spectroscopically confirmed. We use 9 as the number of substructures and show the current uncertainty with an error bar to 30 in Figure 2.

The loose groups might not be single bound systems but projections of filaments of galaxies (Hernquist et al. 1995) or a superposition of multiple structures (Zabludoff & Mulchaey 1998b). At the moment, the loose groups are the main objects that we have in the transition region intermediate between overmerged systems and clusters. Figure 2 is sparsely populated but argues for substantial variation of properties of systems with velocity dispersions of 300–400 km s\(^{-1}\).

4. DISCUSSION

What is the origin of the fossil groups? The similarity of their cumulative galaxy distribution to that of the Local Group (Fig. 1, left panel) suggests that they are the end result of the merging of \( L^* \) galaxies in low-density environments (Jones et al. 2003). The giant elliptical in RX J1340.6+4018 has no spectral features that would indicate recent star formation. Hence, the last major merger must have occurred several gigayears ago (JPF00).

Although the substructure functions of fossil groups and the Local Group are similar, the merger of the Milky Way and the Andromeda galaxy will not form an X-ray–dominated fossil group. The mass of the merged Local Group will be \( \approx 3 \times 5 \times 10^{12} M_\odot \) (Kahn & Wolter 1959) within 300 kpc with \( V_{\text{max}} \approx 290 \text{ km s}^{-1} \), 10% higher than Andromeda and significantly less than observed fossil groups. Merging will not change the circular velocity of the satellites, although they will change morphology and then fade. The result will look more like Centaurus A, which has a substructure function like the Local Group, with an elliptical galaxy at the middle but no X-ray emission and a total mass that is less than fossil groups (Karachentsev et al. 2002). Additional “two by two” hierarchical merging would make a system that matched the optical properties of a fossil group, but it is not clear why overmerging would propagate up the hierarchy to produce fossil groups.
while clusters like Virgo have galaxies of the same luminosity as those that are missing in fossil groups.

X-ray halos in fossil groups and clusters are another problem (Mulchaey 2000). In general, it is difficult to keep all the gas coming from at early times and becoming a part of the galaxies. Since Virgo has extensive X-ray emission while Fornax has a paltry intracluster medium, we have all four combinations of systems that are overmerged or have abundant substructure together with those with abundant or very little intracluster medium. It might well be that having fossil groups among the progenitors of a cluster is key to producing their X-ray emission.

Dynamical friction and merging are not a general solution to the overmerging problem. Clearly, these dynamical effects were included in the full numerical simulations that first highlighted the problem in the CDM model. Any specific substructure function evolves in the same way, by dynamical friction and merging independent of the parent mass. The dynamical friction timescale \( t_{df} \) is proportional to the crossing time of a system \( t_{c} \) divided by the fractional mass of the sinking object [e.g., \( t_{df} \approx 0.05 t_{c} / (M_{sinker}/M_{parent}) \)]. The crossing time of all virialized halos is the same. Furthermore, the fractional mass of the sinking satellite is a function of the variable \( V_{c}/V_{parent} \), in the substructure function, and the tidal radius of the satellite, which is determined by its orbital pericenter as a fraction of the virial radius \( r_{peri}/r_{virial} \). All of these quantities scale with parent mass such that the evolution of the substructure function is independent of the mass of the parent halo. Dynamical friction can be important in promoting the merger of the largest objects in less than one Hubble time within a parent halo, but dynamical friction alone will not create substructure functions that are different for different parent masses. Of course, galaxies could have had a long time to evolve by dynamical friction, but this will not affect the substructure function below \( V_{c}/V_{parent} \) of 0.2.

What mechanisms could explain the substructure function of fossil groups? The first thought might be merely cosmic variance. The top panel of Figure 2 shows the variance in the groups selected from the SDSS (Desai et al. 2004). The figures in Desai et al. (2004) show that this variance is already 2–3 times greater than observed in the simulation of a (100 Mpc)\(^3\) volume simulated by Reed et al. (2003). The fossil groups lie well outside of the variation seen in the large simulation, but they are rare enough that a larger volume is required to be definitive.

One might extend the proposal of Hayashi et al. (2003), who argue for shifting points to the right and then blowing the baryons out of the smallest objects. While gas ejection is at least 10 times as much energy to blow the gas out of the missing galaxies in fossil groups. Furthermore, the gas ejection must also be tuned to the environment, since the same galaxies appear at the predicted frequency in clusters and the field. We have no evidence that \( L^\star \) galaxies are fragile in either of these environments. The same tuning argument is a severe constraint on solutions that alter the initial cosmic fluctuation spectrum. Star formation could be suppressed at a higher energy scale in fossil groups by appealing to intense bursts of star formation, as seen in starburst galaxies at high redshift, or by appealing to the power of a supermassive black hole. The comoving number densities of the ultraluminous infrared starburst galaxies at high redshift roughly match the number densities of the halos predicted at the same redshift by hierarchical merging, leading to the speculation that there is a starburst galaxy in every halo with mass \(~10^{13} M_\odot\) (Somerville et al. 2001). These halos will also be the progenitors of objects the size of fossil groups and larger.

Such an energy injection could also create the reservoir of gas needed for large clusters as well as the observed entropy floor in that gas. As substructure is suppressed, gas falling into the deep potential well of a massive dark cluster will be more effectively heated in an accretion shock. This could enhance substructure suppression and boost the fraction of baryons that settle into a single luminous galaxy. However, the presence of intracluster gas does not appear to be related to the substructure function, as we see all combinations of X-ray emission and substructure functions in our small sample of systems. It is also not clear why energy input was so effective at suppressing substructure in a fossil group but so ineffective in Fornax and Virgo, which have the powerful sources Fornax A and M87.

Fossil groups offer a better environment to test these hypotheses than galaxies that are counterparts to the Milky Way. If the galaxies have been altered in fossil groups, they must be a factor of 10 fainter than expected from their dark matter mass. As a result, they should have velocity dispersions that are anomalously high by nearly a factor of 2.

Gravitational lensing provides three possible tests. M99 suggested direct detection of mass clumps using the brightness ratio of lensed images. With this technique, Dalal & Kochanek (2002) used a sample of isolated elliptical galaxies that are likely the centers of fossil groups. They found that a few percent of the mass in halos is in clumps with masses in the range of \( 10^{6}–10^{7} M_\odot \), which is a factor of a few below what is seen in simulations (M99; Klypin et al. 1999; Ghigna et al. 2000). However, Zentner & Bullock (2003) found that Dalal & Kochanek’s model underestimated the substructure, since they placed substructures uniformly in the halo rather than allowing for stripping and destruction in the central regions, where they had the greatest sensitivity. There are other consequences associated with clumps that are more massive than \( 10^{9} M_\odot \). In the strong-lensing case, the positions of images will shift and betray individual clumps rather than just their statistical properties. This was not seen by Dalal & Kochanek (2002). Shifts in the center of mass may also be seen with weak-lensing maps. Here one would compare the centers defined by the brightest galaxy, the X-ray emission, and the lensing map. If there is significant clumping, the brightest galaxy will be displaced from the center of mass defined by the other two. The center of the X-ray emission generally agrees with the location of the brightest galaxy (Mulchaey 2000), but the lensing map should be a more sensitive test.

5. CONCLUSIONS

Gas processes have been invoked to explain the absence of dwarf satellites in the Milky Way and the field compared to CDM predictions. However, we now find that overmerging persists in the larger mass scale of fossil groups, where galaxies as massive as the Milky Way and the Large Magellanic Cloud are “missing,” although they appear at the predicted abundance in both the field and clusters of galaxies. Figure 2 shows that the overmerging behavior is more dependent on the mass of the parent halo than on the mass of the satellite, although this could be a result of our limited sample size. We have pointed to some key observations that can resolve whether this is a result of energetic phenomena or of an unknown source that is closely tied to the mass scale of the parent halo. To resolve this
issue, we need more systems with velocity dispersions in the range of 300–400 km s$^{-1}$. For the present data, overmerging behavior seems to be the generic behavior for objects with $T \leq 1$ keV.

We would like to thank Simon White, Andi Burkert, Chris Kochanek, and Claudia Mendes de Oliveira for useful discussions and comments. G. L. acknowledges support from the US National Science Foundation.

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