DISSIPATIONLESS MERGING AND THE ASSEMBLY OF CENTRAL GALAXIES

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ABSTRACT

We reanalyze the galaxy-mass correlation function measured by the Sloan Digital Sky Survey to obtain host dark matter halo masses at galaxy and galaxy-group scales. We extend the data to galaxy clusters in the 2MASS catalog and study the relation between central galaxy luminosity and halo mass. While the central galaxy luminosity scales as \(\sim M^{0.7}\) to \(M^{0.8}\) at low masses, the relation flattens to shallower than \(\sim M^{0.3}\) above \(\sim 4 \times 10^{13} M\odot\). The total luminosity of galaxies in the halo, however, continues to grow as a power law \(\sim M^{0.75-1.0}\). Starting from the hypothesis that the central galaxies grow by hierarchical merging (“galactic cannibalism”), we develop a simple model for the evolution of their luminosities as a consequence of the accretion of satellite galaxies, tracking the merging of dark matter halos. The luminosity-mass relation flattens when the timescale on which dynamical friction induces orbital decay in the satellite galaxies exceeds the age of the dark matter halo. Then the growth of the central galaxy is suppressed, as it can cannibalize only the rare, massive satellite galaxies. The model takes the dependence of the total luminosity of galaxies in a halo on its mass and the global galaxy luminosity function as input and reproduces the observed central galaxy luminosity-mass relation over 3 decades in halo mass, \(10^{12}-10^{15} M\odot\). The success of the model suggests that gas cooling and subsequent star formation did not play an important role in the final assembly of central galaxies from sub-\(L_*\) precursors.

Subject headings: cosmology: observations — cosmology: theory — galaxies: clusters: general — galaxies: formation — galaxies: fundamental parameters

Online material: color figure

1. INTRODUCTION

The standard picture of galaxy formation (e.g., Rees & Ostriker 1977; White & Rees 1978) postulates that as dark matter halos virialize, the gas inside the halos is heated to the virial temperature and then cools to form galaxies. While the dearth of faint dwarf galaxies can be explained in semianalytic models with feedback mechanisms that expel gas from small dark matter halos at early times, these mechanisms eventually yield an overabundance of bright galaxies, as the expelled gas eventually cools in massive halos to form luminous galaxies (see, e.g., Benson et al. 2003).

Motivated by the discovery that the temperature distribution of gas in virializing halos in numerical simulations is bimodal (Keres\(\) et al. 2004), and by the lack of evidence for significant cooling flows in galaxy clusters (e.g., Fabian et al. 2001), Binnney (2004) suggested that only the cold component cools to form galaxies, while the hot component remains at the virial temperature. One mass scale characterizing galaxy formation is that below which shocks cannot be sustained, the gas never becomes hot, and all the gas in the cold component streams to form a galaxy. In models of shock formation, this critical mass is \(M_{\text{shock}} \sim (1-6) \times 10^{11} M\odot\) (Dekel & Birnboim 2004).

Since galaxies do not continue to grow significantly by accreting hot gas in this model, the dominant process that induces stellar mass growth is the accretion of other galaxies. Thus, the galaxy growth on scales above \(M_{\text{shock}}\) is primarily governed by the dissipationless merging of preexisting galaxies, though a leftover fraction of cold gas can trigger additional star formation during the merging. Indeed, observations indicate that star formation in mergers contributes insignificantly to the mass budget of the final galaxy (van Dokkum et al. 1999; Conselice et al. 2001). The merging of galaxies tracks the hierarchical assembly of the host dark matter halos (Ostriker & Tremaine 1975; Merritt 1985; Dubinski 1998). Here a second characteristic scale is expected, which is associated with the efficiency by which galaxies accrete other galaxies. Above this second scale, smaller galaxies that have merged into a larger halo do not have enough time to reach the halo center and aggregate into one final central galaxy.

In § 2, we extract the dependence of central galaxy luminosity on halo mass in galaxies imaged in the Sloan Digital Sky Survey (SDSS) and Two Micron All Sky Survey (2MASS). In § 3, we derive a relation between the luminosity of the central galaxy and the mass of its host dark matter halo from first principles. The relation fits the data from galaxy scales, \(\sim 10^{12} M\odot\), to cluster scales, \(\sim 10^{15} M\odot\). In § 4, we discuss consequences for the formation of galaxies on scales above \(M_{\text{shock}}\). We adopt the current concordance cosmological model consistent with results from the Wilkinson Microwave Anisotropy Probe (Spergel et al. 2003).

2. THE GALAXY–DARK MATTER CORRELATION FUNCTION

The luminosities of central galaxies in clusters and groups can be extracted directly from IR imaging data in 2MASS, while the masses can be inferred from the X-ray temperatures (Lin & Mohr 2004). As a direct mass measurement of the halo mass is impossible at galaxy scales, we extract the masses from the measurements of weak gravitational lensing shear around foreground galaxies. The measurements from SDSS (York et al. 2000), binned as a function of the galaxy luminosity (Sheldon et al. 2004), allow one to extract the masses of the host halos of the foreground galaxies, similar to Guzik & Seljak (2002) and Yang et al. (2003).

In galaxy-galaxy lensing, one first measures tangential shear around foreground galaxies as a function of the projected distance \(R\) and then constructs the excess surface density, \(\Delta \Sigma(R)\)
\[ \Sigma(r) - \bar{\Sigma}, \text{ where } \bar{\Sigma}(R) = 2R^{-2} \int_0^p \Sigma(R')R'dR' \] is the mean surface density within \( R \). This surface density can be expressed in terms of the galaxy-mass correlation function, \( \xi_{gm}(r) \), via \( \Sigma(R) = \bar{\rho} \int \xi_{gm}(R')R'dR' \). The correlation function is related to the cross power spectrum through a Fourier transform, \( \xi_{gm}(r) = (2\pi)^{-1} \int \tilde{P}_{gm}(\mathbf{k})d\mathbf{k} \). Within the halo paradigm (Cooray & Sheth 2002), the cross power spectrum can be constructed from the halo mass function \( dn/dM \) (Jenkins et al. 2001), the density profile of a halo \( \rho(r, M) \), and information on how halos are distributed with respect to the linear density fluctuations. We assume that the density profile is the NFW function (Navarro et al. 1997), with the concentration parameter given by Bullock et al. (2001).

To characterize multiple galaxies sharing the same halo, we use the halo occupation number description (Kravtsov et al. 2004). We distinguish between central and satellite galaxies. The satellites are described by a mean occupation, \( \langle N_{sat} \rangle = [M - M_0]/M_0 \), where the parameters \( M_0 \sim 10^{12}-10^{13} M_\odot \), \( M_1 \sim 10^{10}-10^{11} M_\odot \), and \( \lambda \sim 1 \) are given in Table 1 of Zheng et al. (2004). On the scales of interest, the central occupation number is unity, \( \langle N_{cen} \rangle \sim 1 \).

The central and satellite galaxy contributions to the cross power spectrum are

\[
P_{gm, cen}(k) = \frac{1}{n} \int \frac{M}{\bar{\rho}} \frac{dn}{dM} \langle N_{cen} \rangle u(k, M) dM,\]

\[
P_{gm, sat}(k) = \frac{1}{n} \int \frac{M}{\bar{\rho}} \frac{dn}{dM} \langle N_{sat} \rangle u(k, M) u_l(k, M) dM.\]

Here \( u(k, M) \) and \( u_l(k, M) \) are the normalized Fourier transforms of the halo and galaxy density profiles, respectively. For simplicity, we set \( u_l(k, M) = u(k, M) \). We also define the average density of mass, \( \bar{\rho} = \int (dn/dM) dM \), and galaxies, \( \bar{n} = \int (N_{cen}/dn/dM) dM \), where \( j \) distinguishes central and satellite galaxies. We use the data extending to 1 h\(^{-1}\) Mpc in radius. This allows us to ignore the large-scale clustering between halos (e.g., the correlation between galaxies in one halo and dark matter in another), though is an important contribution at \( \sim 10 \) h\(^{-1}\) Mpc scales (see Fig. 1a).

In Fig. 1a, we show the Sheldon et al. (2004) measurement of excess surface density in the \( z \) band, separated into three luminosity bins. Overlaid are the best-fit models for \( \Delta \Sigma(R) \) calculated as described above. Given that the concentration parameter depends on mass, the fitting is done over a single parameter, the halo mass. In Fig. 1b, we compile our mass estimates, as well as the data from Lin & Mohr (2004) for central galaxy luminosities in groups and clusters, and the total luminosities in these systems (Lin et al. 2004). The logarithmic slope of the relation between the halo mass and the central galaxy luminosity is different at low and high mass scales. At the low-mass end, the fits to the galaxy-galaxy lensing data suggest \( L_c \propto M^{0.8} \) to \( M^{0.9} \), consistent with Guzik & Seljak (2002) and Yang et al. (2003). At the high-mass end, the relation is shallower, \( L_c \propto M^{0.5} \) (Lin & Mohr 2004), similar to the scaling in the 2dF galaxy group catalog (Yang et al. 2005).

The relation between the halo mass and the total luminosity of galaxies in the halo, however, remains a power law over 3 decades in mass, \( L_{tot} \propto M^\beta \) with \( \beta \sim 0.85 \). Such a power law is consistent with the dependence of the stellar mass-to-light ratio on stellar mass, \( M_{stellar}/L \propto M_{stellar}^{a/b} \) (Bender et al. 1992). At the high-mass end, the power law could also be related to the mass function of subhalos within a halo of mass \( M \). With the scaling \( N_s(m) |M|dm \sim m^\gamma M^{-1} dm \) for the number of subhalos with masses between \( m \) and \( m + dm \) (Vale & Ostriker 2004), the total luminosity of the parent halo scales as \( L_{tot}(M) \propto \int N_s(m) |M|L(m)dm \sim M^{-\gamma} \), where \( L(m) \) is the luminosity of the galaxy in the subhalo, which vanishes in subhalos too small to contain galaxies. The slope of the \( L_{tot}(M) \) relation is then consistent with the numerical estimates, \( a \approx 1.8-1.9 \) (De Lucia et al. 2004).
3. CENTRAL GALAXY LUMINOSITY–HALO MASS RELATION

We now calculate the rate at which the luminosity of the central galaxy grows due to the accretion of satellite galaxies. The accretion is moderated by the dynamical friction timescale, \( t_{df} \), on which a satellite galaxy sinks in the potential of the primary halo. The effective total mass of a satellite galaxy is augmented by the bound dark matter mass left behind from the epoch when the satellite was at the center of an isolated halo. The central galaxy luminosity thus grows at the rate

\[
\frac{dL_\star}{dt} = \int_{t_{\min}}^{t_c} \frac{dN}{dL_\star, t_{df}(L_\star)} dL_\star, 
\]

where \( N(L) \) is the number of satellite galaxies with luminosities less than \( L \) (the integrated luminosity function) and \( L_{\min} \) is evaluated below.

A satellite halo experiences torque \( T_g = |r \times F_g| \), where \( F_g \) is the force of dynamical friction, \( |F_g| = 4\pi f_{df} G^2 \times M(r) \rho(r) \ln(\Lambda) \nu^2 \) (Chandrasekhar 1943; but see Tremaine & Weinberg 1984). For circular orbits, the velocity of the satellite is the circular velocity in the primary halo, \( v_\star = [GM(r)/r]^1/2 \); \( M(r) \) is the mass of the primary halo contained within this radius; \( \rho(r) \) is the density; \( M_r \) is the mass of the satellite contained within the radius \( r \), measured from the center of the satellite, at which the satellite is tidally truncated; and \( \ln \Lambda \) is the Coulomb logarithm. In numerical simulations of satellites in halos (Bontekoe & van Albada 1987; Velázquez & White 1999; Fellhauer et al. 2000), \( \ln \Lambda \approx 2 \); for an explanation of small \( \ln \Lambda \), see Appendix A of Milosavljević & Merritt (2001). The numerical factor \( f_{df} \) is of order unity and depends on the orbit of the satellite and on the orbital phase-space distribution of dark matter. The satellite is tidally truncated at the radius where its average density equals that of the host halo within the orbit of the satellite, \( M(r)/r^3 \).

The satellite spirals toward the center of the primary halo on a timescale \( t_{df} = (M/T_g)(dJ/d \ln r) \), where \( J \) is the specific angular momentum of the orbit. In the outer parts of NFW halos, \( dJ/d \ln r \approx 0.7–1 \). The timescale is the longest when the satellite has just entered the virial radius of the primary halo, and thus we evaluate \( t_{df} \) at \( r = r_{\text{vir}} \); the average densities of the two halos when they are touching at the virial radii, \( \bar{n} \), are both equal to 200 times the universal matter density, while the density at radius \( r_{\text{vir}} \) is a factor of \( \sim 4–7 \) smaller than the average density, depending on the halo concentration. We denote the ratio \( \bar{n}/\rho(r_{\text{vir}}) \equiv \eta \approx 5 \). If the orbit of the satellite is eccentric when it first enters the primary, the effective density that gives rise to the dynamical drag is larger than at the edge of the halo. We do not explore these complications and subsume the dependence on the halo orbit in the factor \( f_{df} \). The dynamical friction time then equals

\[
\frac{1}{t_{df}} = \frac{1}{2\sqrt{3\pi f_{df}}} \ln \Lambda \frac{1}{\sqrt{G\bar{n} M_\star}}. 
\]

Therefore, \( t_{df} \) exceeds the dynamical time of the primary halo \( (G\bar{n})^{-1/2} \) by a factor proportional to the mass ratio of the two halos.

The luminosity function of galaxies sharing the same dark matter halo can be modeled as

\[
\frac{dN}{dL} = \Phi_* \left( \frac{L}{L_*} \right)^\alpha e^{-L/\bar{L}_s}, 
\]

where \( L_* \approx 8.3 \times 10^{10} L_\odot \) is a characteristic luminosity scale, \( -1.3 \leq \alpha \leq -0.8 \) (Lin et al. 2004 and references therein; \( \alpha \approx -1.0 \) is appropriate for field galaxies and \( \alpha \approx -0.8 \) for clusters), and \( \Phi_* \) is a normalization factor set by the requirement that the total luminosity in the cluster equals \( L_* \). In general, \( L_* \) is also a function of the halo mass and environment (e.g., Croton et al. 2005), but we ignore this subtlety. Thus, \( \Phi_* = L_{\text{tot}}(M)/L_{\text{tot}}(2 + \alpha) \). Substituting equations (3) and (4) into equation (2), we obtain

\[
\frac{dL_\star}{dt} = 2\sqrt{3\pi f_{df}} \ln \Lambda \frac{L_{\text{tot}}(M)}{H^2} \frac{\sqrt{\bar{n}}}{L^2} \frac{\sqrt{\bar{n}}}{M} \times \int_{L_{\text{min}}}^{L_c} \left( \frac{L}{L_*} \right)^\alpha e^{-L/\bar{L}_s} \frac{M(L) L_c}{dL} dL_\star, 
\]

where \( M(L) = \) the dark matter mass associated with the satellite of luminosity \( L \), before tidal stripping and \( L_{\text{min}} \leq L \leq L(M) \) is the luminosity associated with the smallest satellite, having mass \( M_{\text{min}} \), that can be accreted to the halo center in a growth time of the primary halo, \( 1/\tau_{\text{vir}} \), where \( \tau \approx 1 \) (Wechsler et al. 2002). The minimum mass can be then be obtained from the condition \( t_{df}(M = M_{\text{min}}) = 1/\tau_{\text{vir}} \). Assuming that stellar mass grows by mergers only, \( \delta M(t)/M(t) \sim 0 \), we divide equation (5) by \( dML/M \) to obtain the rate of increase in luminosity of the central galaxy per increase in the halo mass:

\[
\frac{dL_\star}{dt} = \frac{30\sqrt{3\pi f_{df}} \ln \Lambda \frac{L_{\text{tot}}(M)}{H^2} \frac{\sqrt{\bar{n}}}{L^2} \frac{\sqrt{\bar{n}}}{M} \times \int_{L_{\text{min}}}^{L_c} \left( \frac{L}{L_*} \right)^\alpha e^{-L/\bar{L}_s} \frac{M(L) L_c}{dL} dL_\star, 
\]

where we have used the virial density relation to critical density \( \bar{n} = 200(3\Omega_{m}H_0^2/8\pi G) \) with \( \Omega_m \approx 0.3 \).

To obtain a rough idea about the meaning of equation (6), we note that we are interested in the \( L_\star \) relation for galaxies brighter than \( L_* \). Then the integral can be approximated by the integrand evaluated at the lower limit and multiplied by \( L_* \). Since \( M_{\text{min}} = \mu M \) with \( \mu \equiv \eta/300\sqrt{3\pi f_{df}} \ln \Lambda \),

\[
\frac{dL_\star}{dt} \approx 1 \times \frac{L_{\text{tot}}(M)}{M} \left( \frac{L_{\text{tot}}(M)}{L_*} \right)^{1+\alpha} e^{-L/\bar{L}_s}, 
\]

4. RESULTS AND DISCUSSION

We integrate the delay differential equation (7) numerically from small to large masses, where at the small masses we assume that \( L(M = L_{\text{sat}}(M)) \), where \( L_{\text{sat}}(M) = L(M/M_\star)^7 \) with \( M_\star \approx 3.5 \times 10^{12} M_\odot \). In the regime \( L(M) \ll L_* \), where the exponential factor can be neglected, we obtain \( L(M) \sim L_\star (M/M_\star)^{7/\alpha} \), that is, the luminosity of the central galaxy is a power law, similar to that describing the total luminosity of
galaxies in the halo. On the scale $M_{\text{crit}} \sim M_\star/\mu$, the power law breaks and the growth of the luminosity is suppressed.

Using $\alpha = -1$, $\beta = 0.85$, $f_{\text{eq}} = 1$, $\tau = 1$, $\eta = 5$, $\Omega_m = 0.3$, and $\ln \Lambda = 2$, we estimate $\mu \approx 0.16$. As discussed above, the evaluation of the exact value of $\mu$ is beyond the scope of this analysis and may vary from one halo to another. We compare the predictions of the model by plotting $L_c(M)$ obtained by direct integration of equation (7) over the data in Figure 1b. Because of the uncertainty in the precise value of $\mu$, we present curves for $\mu = (0.05, 0.1, 0.2)$. For $\mu = 0.1$, the critical mass scale of the luminosity growth retardation is $M_{\text{crit}} \approx 3 \times 10^{11} M_\odot$, which is naturally associated with the halos in which the timescale on which the satellites merge with the central galaxy is equal to the age of the primary halo. This is an additional fundamental scale characterizing galaxy formation. This scale is not evident in the luminosity function, as the additional fundamental scale characterizing galaxy formation.

As evident in Figure 1b, $M_{\text{crit}}$, identified with the break in the $L_c-M$ relation, is sensitive to the value of $\mu$, which is in turn sensitive to the precise calibration of the dynamical friction force, as well as to the orbit of the satellite at the point of initial entry into the primary halo. The value of $\mu$ is also sensitive to $\tau$, the dynamical age of the primary halo. Both uncertainties plausibly give rise to a factor of 2 variation in $\mu$. This can explain the large scatter in the observed central galaxy luminosity–halo mass relation in luminous groups and clusters.

The successful derivation of the relation from first principles and without reliance on detailed numerical simulations or semianalytic models encourages us to propose several general conclusions. In semianalytic models of galaxy formation that are based on efficient gas cooling, luminous galaxies are generally overabundant (‘‘the overcooling problem’’; e.g., Benson et al. 2003). At the same time, the luminosity function at the luminous end is dominated by central galaxies above $L_\star$. Given that we have explained the luminosity growth of such galaxies through dissipationless merging, it is unlikely that additional cooling inside groups and clusters contributes significantly to their stellar mass budget. Thus, gas cooling must be generally suppressed, either through feedback or heating, on mass scales ranging widely from $L_\star$ galaxies to clusters (see also Maller & Bullock 2004). While the exact mechanism of cooling suppression remains a mystery, we believe that it is not restricted to clusters with temperature above $\sim 1$ keV, as suggested by Fabian (2005).

Our results support the paradigm for the formation of giant galaxies with two fundamental scales, namely, that related to the efficiency of cooling, $\sim (1–6) \times 10^{11} M_\odot$ (Dekel & Birnboim 2004), and that related to the efficiency of merging, $\sim (1–6) \times 10^{11} M_\odot$. It appears that the conditional luminosity function “knows” about both scales (Yang et al. 2003, 2005). The standard $M_\star$ galaxies, which correspond to $L_\star$ galaxies on the luminosity scale, belong between these scales. Since $M_{\text{crit}}$, interpreted as the scale at which the $L_c-M$ relation exhibits a break, is a consequence of the drop in the merging efficiency, it also may be possible to explain $M_\star$ and $L_\star$ on the basis of dissipationless merging.

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