MERGER VERSUS ACCRETION AND THE STRUCTURE OF DARK MATTER HALOS

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ABSTRACT

High-resolution N-body simulations of hierarchical clustering in a wide variety of cosmogonies show that the density profiles of dark matter halos are universal, with low-mass halos being denser than their more massive counterparts. This mass-density correlation is interpreted as reflecting the earlier typical formation time of less massive objects. We investigate this hypothesis in the light of formation times defined as the epoch at which halos experience their last major merger. Such halo formation times are calculated by means of a modification of the extended Press & Schechter formalism that includes a phenomenological frontier, \( \Delta_m \), between tiny and notable relative mass captures leading to the distinction between merger and accretion. For \( \Delta_m \sim 0.6 \), we confirm that the characteristic density of halos is essentially proportional to the mean density of the universe at their time of formation. Yet, proportionality with respect to the critical density yields slightly better results for open universes. In addition, we find that the scale radius of halos is also essentially proportional to their virial radius at the time of formation. We show that these two relations are consistent with the following simple scenario. Violent relaxation caused by mergers rearranges the structure of halos leading to the same density profile with universal values of the dimensionless characteristic density and scale radius. Between mergers, halos grow gradually through the accretion of surrounding layers by keeping their central parts steady and expanding their virial radius as the critical density of the universe diminishes.

Subject headings: cosmology: theory — galaxies: formation — galaxies: halos — galaxies: interactions

1. INTRODUCTION

High-resolution N-body simulations of hierarchical clustering in the standard cold dark matter (CDM) cosmogony carried out by Navarro, Frenk, & White (1996) show that the spherically averaged equilibrium density profiles of dark matter halos with masses ranging from dwarf galaxy to rich cluster scales are well fitted (see however Moore et al. 1998) by the formula

\[
\frac{\rho(x)}{\rho_{crit}} = \delta_c \frac{x_s^3}{x(x + x_s)^3}. \tag{1}
\]

In equation (1), \( \rho_{crit} \) is the critical density of the universe, \( x = r/R \) is the radius scaled to the so-called virial radius \( R \), and \( \delta_c = \rho_c/\rho_{crit} \) and \( x_s = r_s/R \) are dimensionless parameters giving the characteristic density and scale radius, respectively, of the density profile. These latter two parameters are linked through the relation

\[
\delta_c = \frac{200}{3 \left[ \ln(1 + x_s^{-1}) - (1 + x_s)^{-1} \right]}, \tag{2}
\]

arising from the steadiness condition that the mean density within \( R \) is equal to \( 200 \times \rho_{crit} \). Thus, the dimensional density profile of a halo with mass \( M \) at a given time \( t \) (the latter two quantities fixing the values of \( R \) and \( \rho_{crit} \) in a given cosmogony) is governed by one single free parameter. Note that the inverse of \( x_s \) is a direct measure of the halo concentration.

More recently, Navarro, Frenk, & White (1997, hereafter NFW), and in independent work, Cole & Lacey (1997) and Tormen, Bouchet, & White (1997), have shown that equation (1) provides equally good fits to the density profile of dark halos in a number of other cosmogonies, including flat and open models, with or without a cosmological constant, and with different initial power spectra of Gaussian density fluctuations. In all the cosmogonies investigated, the parameter \( \delta_c \) has been found to correlate with mass in such a way that low-mass halos are denser than those of high mass. This mass-density correlation is interpreted as reflecting the earlier typical formation time of less massive objects. As shown by NFW, the correlation is well described by a simple model in which the characteristic density \( \rho_c \) of a halo of present mass \( M_0 \) is proportional to the mean density of the universe at the corresponding formation redshift \( z_f \), or equivalently,

\[
\delta_c = \Omega_0 [1 + z_f(M_0)]^{3/2}. \tag{3}
\]

To compute \( z_f(M_0) \), NFW used the expression derived by Lacey & Cole (1993, hereafter LC) in the framework of the Press & Schechter (1974, hereafter PS) prescription for the cumulative probability that the mass of a halo following single \( M(t) \) tracks reduces to some fraction of its present mass, \( f \), taken by NFW as a free parameter. They find that for \( f \leq 0.01 \) the predicted typical mass-density relations fit all their simulations reasonably well for essentially the same proportionality factor \( C \). Although this result strictly refers to present-day halos, it should also apply to halos at any redshift for scale-free cosmogonies and those in which the evolution of structure is close to being self-similar.

In spite of this remarkable result one cannot overlook the fact that the distribution of formation times based on single \( M(t) \) tracks is not fully adequate for estimating the time at which a parent halo reaches, for the first time, a fraction \( f \) of its present mass (cf. LC). Moreover, the fact that \( f \) must be less than or equal to 0.01 poses two problems. First, it leads to an ambiguous definition of the formation time, since a progenitor with \( M < 0.5 M_0 \) is not necessarily along the main lineage. Second, it is difficult to understand how the present structure of a halo can bear any relationship to the epoch in which some progenitor reached such a small
fraction of the current halo mass. More importantly, the definition of the formation time in the LC clustering model does not distinguish between notable mass increases occurring more or less abruptly in time. Major deviations from equilibrium and subsequent violent relaxation take place only when halos of comparable masses merge, while tiny mass captures have a negligible effect on the structure of the capturing systems. Numerical simulations of hierarchical clustering (Cole & Lacey 1997; Thomas et al. 1998) indeed show that halos with no evidence of a recent major merger are in steady state within $R$, despite the fact that they are continually capturing small halos.

Kitayama & Suto (1996) have attempted to describe the formation and destruction of halos within the extended PS prescription by differentiating between notable and tiny relative mass captures. Their model lacks, however, a consistent definition for the formation of halos because all halo captures involved in the same common merger are counted separately as giving rise to different new halos. A similar, but fully consistent, approach has been followed independently by Manrique & Salvador-Sole (1995, 1996, hereafter MS95 and MS96). These authors have developed a semi-analytical clustering model within the framework of the peak formalism, hereafter referred to as the CUSP (confluent system of peak trajectories) model, which distinguishes naturally between major and minor mergers, hereafter simply referred to as (true) mergers and accretion. This allows one to define unambiguously the halo formation and destruction times corresponding, respectively, to their last and next merger. Unfortunately, to be fully satisfactory the CUSP model requires a more accurate expression for the peak-peak correlation at small separations than is presently available (Manrique et al. 1998, hereafter M&CO).

In the present paper, we develop a self-consistent modification of the LC model that, drawing inspiration from the CUSP model, differentiates merger from accretion. This model, which retains the simplicity and good predictive properties of the original model (Lacey & Cole 1994) while including better motivated formation and destruction time estimates, is used to investigate the origin of the empirical mass-density and related mass-radius correlations, as well as their implications for the evolution of halo structure in hierarchical cosmogonies. The paper is organized as follows. The modified LC model is presented in § 2. It is applied in § 3 to the study of the empirical mass-density and mass-radius correlations. The results of this analysis are summarized in § 4.

2. MERGER VERSUS ACCRETION AND THE PS FORMALISM

A halo survives as long as it evolves by accretion or, equivalently, as long as it captures only relatively tiny systems. Otherwise it merges, which automatically leads to its destruction. Note that when a halo is captured by one that is more massive it merges and is destroyed in the event, but the capturing halo may survive provided that the captured mass is relatively small. Only those events in which all the initial halo merge and are destroyed give rise to the formation of new halos.

The preceding definitions do not affect the abundance of halos at a given time, only the description of their growth. It is, therefore, not surprising that the CUSP model, also distinguishing between merger and accretion, predicts a halo mass function (MS95) that is highly similar to the PS one as in the LC model. Accordingly, in the modified LC clustering model we propose, the mass function is equal to the PS mass function

$$N(M, t) = \frac{2}{\pi} \rho_0 \frac{\delta_{\text{coll}}(t)}{M^2 \sigma(M)} \left| \frac{d \ln \sigma}{d \ln M} \right| \times \exp \left[ - \frac{\delta_{\text{coll}}(t)^2}{2 \sigma^2(M)} \right],$$

where $\rho_0$ is the present mean mass density of the universe, $\delta_{\text{coll}}(t)$ is the critical overdensity for collapse at $t$ linearly extrapolated to the present time, and $\sigma(M)$ is the current rms overdensity on spheres encompassing a mass $M$.

The instantaneous merger rate for halos of mass $M$ at $t$ per infinitesimal range of final masses $M' > M$, or specific merger rate, predicted by the CUSP model (MS96) is also close to the corresponding rate predicted by the original LC model, down to some value $\Delta_m$ of the relative captured mass $\Delta M/M \equiv (M' - M)/M$, where it shows a sharp cutoff. This cutoff reflects the fact that, in the CUSP model, captures of small mass halos relative to $M$ are not computed as mergers, but simply contribute to accretion. In contrast, the specific merger rate predicted by the LC model,

$$r_m^m(M \rightarrow M', t) = \frac{2}{\pi} \rho_0 \frac{\delta_{\text{coll}}(t)}{M^2 \sigma(M)} \left| \frac{d \ln \sigma}{d \ln M} \right| \times \frac{1}{[1 - \sigma^2(M)/\sigma^2(M')]}^{3/2} \times \exp \left[ - \frac{\delta_{\text{coll}}(t)^2}{2 \sigma^2(M') - \sigma^2(M)} \right],$$

keeps on increasing monotonically for small $\Delta M/M$ because any mass capture is regarded, in this model, as a merger, and the number density of small mass halos diverges. Following this result we modify the original LC model by including a threshold $\Delta_m$ in the relative mass captured by a halo for such an event to be considered a merger, smaller mass captures only contributing to continuous accretion. With this modification the new specific merger rate takes the form

$$r^m(M \rightarrow M', t) = \begin{cases} 0 & \text{if } M < M' \leq M(\Delta_m + 1), \\ r_m^c(M \rightarrow M', t) & \text{if } M(\Delta_m + 1) < M', \end{cases}$$

while the total mass increase rate for halos of mass $M$ at $t$, $r_{\text{mass}}^m(M, t) \equiv dM/dt$, splits into two contributions, one arising from mergers, or mass merger rate,

$$r_{\text{mass}}^m(M, t) = \int_{M(\Delta_m + 1)}^{\infty} \Delta M r^m(M \rightarrow M', t) dM' - 1,$n

and the other arising from accretion, or mass accretion rate,

$$r_{\text{mass}}^m(M, t) = \int_M^{M(\Delta_m + 1)} \Delta M r_m^c(M \rightarrow M', t) dM'. \quad (8)$$

As shown by M&CO, the mass function, the specific merger rate, and the mass accretion rate determine the
behavior of the entire CUSP model. This is also the case for the modified LC model. The specific merger rate determines the mass merger rate (eq. [7]), as well as the destruction rate of halos with mass \( M \) at \( t \)

\[
r^d(M, t) = \int_{M(\Delta_n + 1)}^{\infty} r^d(M \to M', t) dM'.
\]

(9)

Likewise, the formation rate can be written as

\[
r'[M(t), t] = \frac{d\ln N[M(t), t]}{dt} + r^d[M(t), t]
+ \partial_M r^a_{\text{max}}(M, t)|_{M=M(t)},
\]

(10)

from the conservation equation for the number density of halos per unit mass along mean mass accretion tracks, \( M(t) \), solution of the differential equation

\[
\frac{dM}{dt} = r^a_{\text{max}}[M(t), t].
\]

(11)

Finally, the distributions of formation and destruction times in the modified LC model are given by expressions identical to those in the CUSP model (see M&CO). In particular, the distribution of formation times for halos at \( t_0 \) with masses between \( M_0 \) and \( M_0 + \delta M_0 \), with \( \delta M_0 \) arbitrarily small, takes the form

\[
\Phi_f(t) = \frac{1}{N_{\text{pref}}(t_0)} \frac{dN_{\text{pref}}}{dt}
= r'[M(t), t] \exp\left\{ - \int_{t_0}^{t} r'[M(t'), t'] dt' \right\},
\]

(12)

with \( M(t) \) the mass of these halos at \( t \) calculated along their mean mass accretion tracks. The median of this distribution is adopted as the typical halo formation time.

Before concluding this section, we should clarify the fact that the distinction adopted between merger and accretion is not motivated by the results of \( N \)-body simulations, but obeys the desire to differentiate schematically the dynamic effects on halo structure of tiny and notable relative mass captures. Note also that while the merger cutoff in the CUSP model arises naturally from the peak Ansatz and the assumed distinction between merger and accretion (see MS96), the threshold for merger, \( \Delta_n \), in the present modified LC model is a free phenomenological parameter, which, for simplicity, will be considered independent of \( M \) and \( t \). (one assumption implies the other in scale-free universes).

Strictly speaking, the rearrangement of a halo after the merger of two progenitors depends on the relative gain of energy per unit mass rather than simply on the relative mass increase. However, as the former quantity is largely determined by the latter, this simplifying assumption is justified.

3. THE \( \delta_\ast(M_\odot) \) AND \( x_f(M_\odot) \) CORRELATIONS

Next we investigate the possible origin of the mass-density and mass-radius correlations exhibited by halos in hierarchical universes in the light of the modified LC model developed in the preceding section. To do this we use the numerical data of NFW, which comprises the eight different cosmogonies listed in Table 1. The first column of this table lists the power spectra, while columns (2) and (3) list the values of \( \Omega_0 \) and \( \lambda_0 \equiv \Lambda/(3H_0^2) \), respectively. We list in column (4) the present rms density fluctuation in \( 8 h^{-1} \) Mpc spheres, \( \sigma_8 \). To facilitate the comparison among the cosmogonies, masses are scaled to the values of the present characteristic mass \( M_\odot \), defined through \( \sigma(M_\odot) = \delta_{\text{coll}}(t_0) \), which are listed in column (5) of Table 1. All the models have \( h = 0.5 \), except the LCDM model that has \( h = 0.75 \), with the Hubble constant defined as \( H_0 = 100 h \) km s\(^{-1}\) Mpc\(^{-1}\).

In Figure 1 we show the best fits (by a standard least squares minimization in logarithmic units) to the empirical \( \delta_\ast(M_\odot) \) correlation obtained using the fitting formula (eq. [3]) for three different values of \( \Delta_n \). The value 0.6 corresponds to the best overall fit when \( \Delta_n \) is varied from 0.1 to 0.9 in steps of one-tenth. This value is also favored individually by the three flat power-law spectrum models with \( n = -1, -0.5, \) and 0, which are those that best discriminate among the different predictions. The two open scale-free models favor a value of \( \Delta_n = 0.5 \), while the remaining power spectrum model and the two CDM models favor \( \Delta_n = 0.7 \), although marginally. In other words, as is apparent from Figure 1, a value of \( \Delta_n \sim 0.6 \) gives reasonably good fits in each of the cosmogonies investigated. In contrast, the predictions corresponding to the extreme values 0.1 and 0.9 do not describe the numerical data well in practically any case.

Given the formation time distribution function (eq. [12]) and equation (3) we can readily derive the distribution functions of log \( \delta_\ast \) for any value of \( M_\odot \). Figure 2 shows the distributions obtained in the standard CDM (SCDM) model for five different values of \( M_\odot \); other cosmogonies giving qualitatively similar results. They are in good overall agree-

### Table 1

| \( P(k) \) | \( \Omega_0 \) | \( \lambda_0 \) | \( \sigma_8 \) | \( M_\odot/M_\odot \) | \( C \) | \( \delta_\ast \) | \( x_f \) | \( x_{\delta} \) |
|-----------|-------------|-------------|-------------|----------------|----|-------------|---|--------|
| SCDM ...... | 1.0          | 0.0         | 0.63        | \( 3.08 \times 10^{13} \) | 1.21 \times 10^4 | 1.21 \times 10^4 | 0.173 | 0.229 |
| LCDM ...... | 0.25         | 0.75        | 1.3         | \( 6.31 \times 10^{13} \) | 4.21 \times 10^4 | 3.77 \times 10^4 | 0.291 | 0.285 |
| \( n = 1.5 \) .... | 1.0          | 0.0         | 1.0         | \( 1.47 \times 10^{14} \) | 8.30 \times 10^4 | 8.30 \times 10^4 | 0.204 | 0.223 |
| \( n = 1.0 \) .... | 1.0          | 0.0         | 1.0         | \( 2.48 \times 10^{14} \) | 1.28 \times 10^4 | 1.28 \times 10^4 | 0.169 | 0.181 |
| \( n = -0.5 \) .... | 0.1          | 0.0         | 1.0         | \( 2.82 \times 10^{13} \) | 2.65 \times 10^4 | 1.00 \times 10^4 | 0.188 | 0.184 |
| \( n = 0.0 \) .... | 0.1          | 0.0         | 1.0         | \( 3.40 \times 10^{14} \) | 2.16 \times 10^4 | 2.16 \times 10^4 | 0.135 | 0.148 |
| \( n = 0.0 \) .... | 0.0          | 1.0         | 1.0         | \( 4.19 \times 10^{14} \) | 6.19 \times 10^4 | 6.19 \times 10^4 | 0.088 | 0.096 |
| \( n = 0.0 \) .... | 0.1          | 0.0         | 1.0         | \( 4.56 \times 10^{13} \) | 5.77 \times 10^4 | 1.33 \times 10^4 | 0.126 | 0.165 |

* Implied by \( \delta_{\text{coll}} \).
This indicates that equation (3) also applies to individual halos and that their characteristic density, $\rho_c$, remains essentially equal to $C$ times the mean cosmic density at their time of formation. Note that, according to the PS mass function, low-mass halos are severely underrepresented in the empirical samples with respect to more massive ones, indicating that the selection of the former has been much stricter. In this manner, earlier formation times may have been artificially favored, since the older the halos, the better they satisfy the requirement of having a relaxed appearance. This might explain the slightly smaller scatter shown by the empirical distributions for small mass halos. This effect and the slight bias also introduced by our simple fitting procedure (we have assumed constant, symmetrical errors) might affect to some extent the quantitative results of the fits, but the previous conclusions should prevail.

The values of $C$ listed in column (6) of Table 1 show a much wider variation with the cosmogony (an overall factor 100) than in NFW (only a factor 2; see their Table 1). Although the possible biases mentioned above might in part be responsible for this variation, the marked departure from a hypothetical common value shown by the values of $C$ in open cosmogonies seems real. We have investigated the possibility of reducing the scatter in the $\Omega_0 < 1$ cases by devising a slightly different model that has the added value of providing a straightforward physical interpretation of the empirical mass-density correlation. In the new model, the characteristic density, $\rho_c$, of halos with current mass $M_0$ is assumed to be proportional to the critical density of the universe at their time of formation, instead of to the mean cosmic density at that time. With such a proportionality, not only does $\rho_c$ remain fixed from the time of halo formation, but also the initial value of $\delta_c$ is universal (i.e., independent of mass and time in self-similar universes). From the form this fitting model adopts in dimensionless units

$$\delta_c = \delta_{cf} \frac{\Omega_0}{\Omega[z_f(M_0)]} [1 + z_f(M_0)]^3,$$

it is apparent that the value of $\delta_c$ when halos form is equal to the proportionality factor $\delta_{cf}$.

The best overall fit of the empirical data with the model (eq. [13]) is obtained again for $\Delta_m = 0.6$. As can be seen from Figure 1, the fits in the open cases are slightly better than in the original model (eq. [3]), while the two models give, of course, identical results in the $\Omega_0 = 1$ cases. The overall variation shown by the proportionality factor $\delta_{cf}$ in different cosmogonies has diminished, although a trend of $\delta_{cf}$ with cosmogony is still present. We note that some theoretical studies predict a dependence on the cosmogony of the typical halo density profiles resulting from violent relaxation (e.g., Syer & White 1998).

Equation (2) between the dimensionless parameters $\delta_c$ and $x_t$ tells us that the value of $x_t$ shown by halos at their time of formation, hereafter denoted by $x_{tf}$, is also universal. The values of $x_{tf}$ inferred from those of $\delta_{cf}$ drawn from the previous fits are listed in column (8) of Table 1. The universality of $x_{cf}$ is equivalent to stating that the dimensional scale radius $r_s$ of halos at their time of formation is proportional, with universal proportionality factor equal to $x_{cf}$, to their virial radius $R$ at that epoch. This raises the question: is the scale radius $r_s$ of current halos also proportional, with identical proportionality factor, to their virial radius $R$ at their time of formation? Or, equivalently, does the value
of $r_s$ for current halos of mass $M_0$ coincide with the value this parameter had when they formed, as for $r_v$? The answer to these questions is not trivial since it depends on the relation between the initial and current halo masses, that is, on the typical mass accreted since their formation.

The modified LC model allows us to estimate the mass accreted by halos. Hence, we can readily check the previous proportionality, which in dimensionless units takes the form

$$x_s = x_{sf} \frac{R[M[z_f(M_0), M_0]]}{R(M_0)}.$$  \hspace{1cm} (14)

In Figure 3 we show the results of directly fitting this model to the $x_f(M_0)$ empirical correlation. Once again we find the best overall fit for $\Delta_m = 0.6$. More importantly, the best values of $x_{sf}$, listed in column (9) of Table 1, are in fairly good agreement (just slightly larger on average) with those listed in column (8). Note that, despite the convoluted calculations involved (given a halo of current mass $M_0$ one must first calculate its formation redshift, then, using the modified LC model, its mass at $z_f$, and finally, through the steadiness condition, the corresponding value of $R$), the fits are as good as those obtained for the mass-density correlation.

The agreement, case by case, between the two independent values of $x_{sf}$ given by the correlations $\delta_f(M_0)$ (through eq. [2]) and $x_f(M_0)$ (through our clustering model) supports the overall validity of the modified LC model for $\Delta_m \sim 0.6$, and of the theoretical equations (13) and (14). The physical interpretation of the latter can be summarized as follows: (1) the values of the dimensionless parameters, $\delta_f$ and $x_{sf}$, characterizing the radially averaged density profiles of halos at formation are universal, and (2) the values of the corresponding dimensional parameters, $\rho_f$ and $r_s$, remain fixed as long as halos evolve by accretion.

The fact that for a given halo the values of parameters $\rho_f$ and $r_s$ are set when it forms tells us that the only effect of accretion is the gradual expansion of the halo virial radius $R$ in order to permanently satisfy the steadiness condition. We have directly tested this corollary by comparing the mass increase experienced by halos since their formation predicted by the modified LC model, with the mass increase that results from taking halos with a density profile with the form of equation (1), with fixed values of $\rho_f$ and $r_s$, and progressively increasing the virial radius $R$ as $\rho_{\text{crit}}$ diminishes. As expected, we have found a fair degree of agreement between the two mass evolutions, the maximum departure being less than 35% in any one cosmogony.

4. CONCLUSIONS

The $\delta_f(M_0)$ correlations predicted by the modified LC model for $\Delta_m = 0.6$, assuming equation (3), match the empirical data, as well as the NFW predictions for $f = 0.01$. We therefore confirm, with a more compelling formation time estimate, the claim by these authors that the characteristic density shown by dark halos in equilibrium is proportional to the mean density of the universe at the time they form. We want to stress that while the two different formation time estimates give similarly good fits, this does not imply that the difference in their definitions is merely formal: for any given halo mass, the typical formation redshifts used by NFW are appreciably larger, typically by a factor of 2, than those obtained in the model presented here. We have also shown that the fits for the open models can be improved further if one assumes instead a proportionality with respect to the critical density of the universe at halo formation.

The modified LC model presented in § 2, together with the definitions of halo formation and destruction times with which it deals, relies on the schematic differentiation of the dynamic effects of tiny and notable mass captures. According to this scenario, the structure of halos would be fixed through violent relaxation in the last major merger that they had experienced, while between two consecutive major mergers halos would remain essentially unaltered, mass accretion only producing a progressive expansion of their envelope as new surrounding layers fall in and relax through gentle phase mixing. The results of our analysis in § 3 agree with this simplified description. To be more specific, we have found that the empirical $\delta_f(M_0)$ and $x_f(M_0)$ correlations are consistent with the fact that halos show, at formation, the same density profile with universal values of $\delta_f$ and $x_f$. Until a new major merger takes place, the density profile of halos keeps essentially the same form, although the values of $\delta_f$ and $x_f$ shift as the dimensional characteristic density and scale radius, $\rho_f$ and $r_s$, remain fixed while the virial radius $R$ expands according to the decrease of the cosmic critical density. As shown for the SCDM case by Avila-Reese, Firmani, & Hernández (1998), the latter evolution seems to be a natural consequence of adiabatic-invariant secondary infall. On the other hand, some effect along the lines proposed by Syer & White (1998) might explain the universal halo density profiles resulting from major mergers.

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