ON THE ORIGIN OF EARLY-TYPE GALAXIES AND THE EVOLUTION OF THE INTERACTION RATE IN THE FIELD

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ABSTRACT

Using cosmological N-body simulations of critical and open cold dark matter (CDM) models, we have identified galaxy-sized dark matter halos originated by major binary mergers. Remnants of major merging events between redshift \( z = 1 \) and the present have typically not yet been accreted into groups and clusters, and hence they can be linked to bright early-type field galaxies. The rate of formation of binary merger remnants is \( 1.9 \times 10^{-11}(1+z)^{3.1 \pm 0.2} \) and \( 1.6 \times 10^{-14}(1+z)^{2.5 \pm 0.5} h^{-3} \, \text{Mpc}^{-3} \, \text{yr}^{-1} \) for a critical tilted CDM and an open CDM model, respectively. The average age of these merger remnants is about 6 Gyr, 40\% of the age of the universe. In an open universe, field early-type galaxies formed at \( z < 1 \) by major mergers would account for only \( \sim 5\% \) of the total population of early-type galaxies. This fraction is much higher (\( \sim 55\% \)) in critical models. These results are discussed together with present observational constraints.

Key words: dark matter — galaxies: elliptical and lenticular, cD — galaxies: formation — galaxies: interactions

1. INTRODUCTION

Most elliptical galaxies are well described by the fundamental plane and show the same dynamical properties (Djorgovski & Davis 1987; Faber et al. 1987; Guzmán, Lucey, & Bower 1993). Spheroidal galaxies show a surprisingly tight color-magnitude and Mgb-\( \sigma \) relation, both at present (Larson, Tinsley, & Caldwell 1980; Bower, Lucey, & Ellis 1992) and at higher \( z \) (Ellis et al. 1997; Ziegler & Bender 1997). Moreover, their colors are consistent with the bulk of their stellar population having been formed at \( z > 2 \) (Bender, Ziegler, & Bruzual 1996; Ellis et al. 1997; see also Renzini 1997). These results have also been confirmed recently by Bernardi et al. (1998), who extend the analysis to spheroids in groups and the field, finding similar formation epochs in all environments. Recently, Silva & Bothun (1998) placed a lower limit to the age of field ellipticals of about 5 Gyr.

However, it is also possible to find a number of publications in the literature, including a classic work by Larson et al. (1980), that point out that bright elliptical galaxies residing in clusters have major differences in their stellar populations compared with those residing in the field. Many previous works have argued that field spheroids show a larger scatter in their properties, possibly indicating a younger age as well as a spread in the time of the last major starburst of at least a few gigayears (de Carvalho & Djorgovski 1992; Rose et al. 1994; Longhetti et al. 1998; Abraham et al. 1998). Many field spheroids have a number of features (shells, counterrotating inner disks) believed to be associated with their origin by merger events, which correlate with bluer colors (Schweizer & Seitzer 1992). Strongly disky isophotes are interpreted as a sign of recent star formation in a small central gaseous disk, which could have perhaps been accreted through a merger (de Jong & Davies 1997). Finally, Kauffmann, Charlot, & White (1996) point out that a consistent fraction of galaxies with red colors, possibly in the field, have experienced star formation activity at redshifts less than 1.

These contrasting results have led to the "nature" and "nurture" hypotheses for the formation of early-type galaxies, and specifically of ellipticals (E's). In the "nature" case, star formation occurred at high redshift in a rapid (\( \sim 1 \) Gyr) burst within protogalactic halos that then quickly coalesced to form galaxies with a dominant spheroidal component (e.g., Larson 1974; Arimoto & Yoshii 1987); after this event the stellar population evolved passively. In the case of "nurture," mergers between possibly gas-rich galaxies created spheroidal galaxies as remnants (Toomre & Toomre 1972). These models can be considered two extreme methods of forming E's within the more general hierarchical clustering framework, where dark matter (DM) halos merge continuously through gravitational instabilities, creating larger and larger structures. In the merging process, fragile stellar disks are destroyed and a population of galactic spheroids is created (Baugh, Cole, & Frenk 1996b).

In this paper, we study the environment, rate of formation, and age distribution of early-type galaxies formed by binary mergers at low redshift within the cold dark matter (CDM) scenario. To do this, we identify all major mergers between galaxy-sized halos for redshift \( z < 1 \) and follow their evolution to the present.

Our main objectives are as follows:

1. Estimate the merging rate between galaxy-sized halos in the field and its evolution with redshift.
2. Find the original and present-day environment for the merger remnants. Are they still in the field or have they been accreted by groups or clusters?
3. Estimate the average age of the remnants and compare that with the observationally estimated ages of field and cluster ellipticals.

2. SIMULATION DATA SET

Our simulations followed the evolution of three models: a critical universe (SCDM) \( \Omega_0 = 1, \ h \equiv H_0/(100 \, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1}) \),...
A density contrast within the virial radius of $D$ halos that were formed at more simply, spheroidal-dominated) galaxies by selecting simulations that were most likely to host early-type (or, by a spheroidal component, and they will be classified as created disk is small, these galaxies will appear dominated and the galaxy may have sufficient time to form a new well, the halo is subsequently able to accrete new cold gas, instead the merging event occurs outside a larger potential galaxies is high, merging activity is largely terminated gaseous disk through the secondary infall of cold gas. Once inside DM halos from the cooling of gas and subsequent morphology of linking together close binary systems (see Governato et al. 1997 and SKID, a halo-finding algorithm based on local density maxima.\footnote{A copy can be obtained at http://www-hpcc.astro.washington.edu/tools/}

The SKID algorithm is similar to the DENMAX scheme (Gelb \& Bertschinger 1994). It groups particles by moving them along the density gradient to the local density maximum. The density field and the density gradient are defined everywhere by smoothing each particle with a cubic spline weighting function of a size determined by the distance encompassing the nearest 32 neighbors. At a given redshift, only particles with local densities greater than one-third the mean density of virialized structures at that epoch are “skidded” to the local density maximum. This threshold corresponds roughly to the local density at the virial radius. The final step of the process is to remove all particles that are not gravitationally bound to their parent halo. SKID was designed to find high-contrast density structures within larger halos (see Governato et al. 1997 and Ghigna et al. 1998 for a more complete description). For halos with no resolved internal substructure (i.e., no halos within halos), SKID gives results very similar to FOF. However, SKID does not suffer from the well-known FOF pathology of linking together close binary systems (Governato et al. 1997), and so it is well suited for our project, which requires us to identify binary systems in the process of merging.

We used SKID to identify halos before the merging event and FOF (with a linking length of 0.2 times the average interparticle separation) to identify the descendant halo at the present time. As the descendant halo could be a cluster with significant resolved substructure, SKID would break it into several subcomponents of smaller mass. Since at $z = 0$ we are mainly interested in the total mass of the descendant halo within its virial radius, FOF is the correct halo finder to use. Mergers were identified by finding halos (within the appropriate $V_c$ range) that SKID classified as a single group in one output, but as two separate groups (with a mass ratio $\leq 3:1$) in the preceding output. We further assume that the main galaxies within the parent halos in the merging system (often on very radial orbits; see Governato et al. 1997) will merge on a short timescale, as found in high-resolution $N$-body simulations of binary systems (Barnes 1992; Hernquist 1993).

Particles that belong to the halos identified by our procedure are tracked through subsequent outputs of the simulations to the final time, where the masses of their parent
halos are determined using FOF. Also measured is the present-day halo's environment, which we define as the density within a sphere of $4 \, h^{-1} \, Mpc$.

Because of resolution limitations, we are unable to follow mergers that may occur in the same redshift interval inside structures more massive than galaxy-sized halos (i.e., groups and clusters). However, evidence suggests that in dense environments with high internal velocity dispersion, merging between galaxies is limited (Ghigna et al. 1998).

The selection criteria used in our work may not define the entire class of halos that could host field early-type galaxies at the present time. Some S0's could have originated from a variety of different merging histories, such as multiple small accretions of small satellites or fast two-body encounters inside a group or cluster environment (Miller 1983; Moore et al. 1996; Oemler, Dressler, & Butcher 1997) that led to short, intense starbursts (Poggianti & Barbaro 1996) and consumed their gas content.

In Figure 1 we show a few representative examples of binary mergers. At the present time (and for all three cosmologies; cf. Fig. 2), the majority of halos previously identified as merger remnants within our velocity range still reside in halos of a mass comparable to that at time of their formation, indicating that they have not yet been accreted.

**Fig. 1.**—Evolution of three binary mergers in the TCDM simulation. Boxes are 10 comoving Mpc per side. The present-day environment overdensity for each remnant is $-0.31$, $0.46$, and $2.16$, respectively (see upper right of the rightmost panels). Black particles belong to merging halos or to the remnant. Light gray particles are other nearby halos. Gray particles do not belong to any halo. Left panels show the binaries just before the merging event. Central panels show the remnant shortly after merging, and the right panels show the remnant at present. For each panel the actual redshift is also shown (upper left).
by a larger structure. The great majority of them reside in regions of average density (see Fig. 3). Gravitational clustering did not have enough time to act and move them into larger structures.

On the other hand, we have verified that halos (not necessarily remnants of binary mergers) selected in the same circular velocity interval, but at higher $z$, tend to fall into more massive structures such as groups and clusters. These halos are likely to host the progenitors of cluster ellipticals and are often associated with the so-called Lyman break galaxies (Governato et al. 1998; Coles et al. 1998; Somerville, Primack, & Faber 1998).

It is interesting to compare the number density of our selected halos with existing observational data. The luminosity function obtained by Heyl et al. (1997) gives a number density of $\sim 8 \times 10^{-3} h^3$ Mpc$^{-3}$ for “red + blue E” galaxies with $M_{bj} - 5 \log h < -18$, the magnitude cut roughly corresponding to the circular velocity associated with our $V_c$ lower limit. The magnitude cut was obtained by combining data from Lucey et al. (1997) (velocity dispersions) and Godwin, Metcalfe, & Peach (1983) (magnitudes) and assuming a distance to Coma of $70 h^{-1}$ Mpc. The Marzke et al. (1998) luminosity function gives a comparable comoving number density of E + S0’s in the same luminosity range. If we now sum all major mergers in the range $1 > z > 0$, we obtain a number density of $3.6 \times 10^{-3}$, $4.72 \times 10^{-3}$, and $3.65 \times 10^{-3} h^3$ Mpc$^{-3}$ for SCDM, TCDM, and OCDM, respectively. Recent merger remnants would then represent 50% (for SCDM), 65% (for TCDM), and 5.5% (for OCDM) of the present-day population of early-type galaxies. These numbers must be taken with some caution, because our sample lacks early-type galaxies not originated by major mergers but might include some major-merger remnants that could have grown a significant disk component. Nonetheless, this result suggests that critical cosmologies can produce a large number of field galaxies dominated by a spheroidal component, irrespective of the details of the cosmology (normalization and $\Gamma$ factor). Indeed, a high fraction of early-type galaxies ($\sim 50\%$) reside outside clusters and rich groups (Bernardi et al. 1998). Open models have more problems creating a large number of early-type galaxies through recent major mergers.

This population of field ellipticals will likely contain a younger stellar population compared with their cluster counterpart. However, recent observations of the field population of early-type galaxies (Bernardi et al. 1998) show a systematic age difference of only 1 Gyr compared with cluster spheriodals. To be consistent with observations, these major mergers must involve galaxies with a dominant old stellar component.

4. THE INTERACTION RATE OF BINARY SYSTEMS

There is strong observational evidence (Driver et al. 1995; Glazebrook et al. 1995) that the number of interacting systems grows rapidly with look-back time. New data from the Hubble Deep Field (Abraham et al. 1996; van den Bergh et al. 1996) and recent redshift surveys (Patton et al. 1996) make it possible to measure their number and determine whether the universe was more dynamically active at galactic scales in the past. The data suggest a strong evolution in number density proportional to $(1 + z)^{2.8 \pm 0.9}$ (Patton et al. 1997) or an even steeper $(1 + z)^{4.0 \pm 2.5}$ (Zepf & Koo 1989), or $(1 + z)^{4.4 \pm 1.0}$ as suggested by the number of close galaxy pairs (Carlbarg, Pritchet, & Infante 1994). Similar trends are found in samples of radio-quiet QSOs (Boyle et al. 1993) and IRAS-selected galaxies. Lavery et al. (1996) suggest a rate of interactions of $(1 + z)^{4.5}$, based on the number density of ring galaxies. The value for this trend is very important, given its consequences for the number of merger remnants created and, more generally, for the evolution of the galaxy population and galaxy counts (Ellis 1997; Roche et al. 1996; Baugh et al. 1996a). Figure 4 plots the rate of formation of merger remnants for SCDM, TCDM, and OCDM models. Vertical error bars represent statistical uncertainties that result from the finite size of the sample, and the horizontal span indicates the time interval between successive outputs (of the order of 1 Gyr), effectively our bin size. We find a rate of formation of $1.4 \times 10^{-13}(1 + z)^{4.2 \pm 0.3} h^3$ Mpc$^{-3}$ yr$^{-1}$ for
rather high, but not extreme (recalling that we cut our sample of mergers at $z = 1$), with typical ages of 6, 5.6, and 6 Gyr, corresponding to redshifts of 0.58, 0.53, and 0.534, respectively, for SCDM, TCDM, and OCDM. This is consistent with the lower limits of the stellar population of field ellipticals (Silva & Bothun 1998).

5. DISCUSSION

In this paper we have shown how hierarchical clustering models, namely, CDM, allow for a population of field E’s originated by major binary mergers. In critical models, major mergers between galaxy-sized halos at a redshift $z \leq 1$ could create a significant fraction of the global population of early-type galaxies (up to 60%). These recently formed galaxies do not end up in dense environments. However, most of these galaxies should show ages of several gigayears, even if a significant part of their stellar population was formed during the merger event. Within the CDM framework, the interaction rate in binary galactic systems increases rapidly in the past—qualitatively consistent with observations—with critical models showing a faster evolution.

Recent techniques based on line-strength indices are able to evaluate the epoch of the last starburst with a precision of a few gigayears (Dorman & O’Connell 1996; Bressan, Chiosi, & Tantalo 1996; de Jong & Davies 1997; Longhetti et al. 1998) and disentangle the time evolution from the metal abundances of the stellar populations. These methods will prove invaluable in tracing the origin of early-type galaxies in different environments and will provide a larger database to test theories of galaxy formation. Future detailed simulations that include hydrodynamics and star formation processes will allow us to make more robust and quantitative predictions about the origin and evolution of galaxies within the hierarchical clustering scenario.

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FIG. 4.—Rate of formation of major mergers in the range $0 < z < 1$ as a function of redshift for SCDM (dotted line), TCDM (solid line), and OCDM (dashed line). Lines are best fits in the form $(1 + z)^{3.1 \pm 0.2} h^3$ Mpc$^{-3}$ yr$^{-1}$ for SCDM, and $1.6 \times 10^{-14}(1 + z)^{2.5 \pm 0.4}$ Mpc$^{-3}$ yr$^{-1}$ for the open CDM model. Merging rates obtained from this work are in fair agreement with previous analytical predictions by Carlberg (1990). Our selected sample of halos should host luminous galaxies, which in turn should be preferentially selected in samples containing higher redshift galaxies. As suggested by detailed numerical simulations, they should form a luminous starburst remnant when the galaxies inside each halo actually collide and merge (Mihos & Hernquist 1994). It is not yet clear how QSOs and starburst galaxies, of which the number density is found to increase with redshift, are directly related to interactions and mergers. However, our results suggest a general agreement of CDM models with the observed trend. The average formation time of this population of field ellipticals is then...
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