Carnegie Observatories Astrophysics Series, Vol. 3:
Clusters of Galaxies: Probes of Cosmological Structure and Galaxy Evolution, 2004
ed. J. S. Mulchaey, A. Dressler, and A. Oemler (Cambridge: Cambridge Univ. Press)

Galaxy Groups at Intermediate Redshift and the Mechanisms of Galaxy Evolution

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Abstract

The CNOC2 intermediate-redshift spectroscopic survey is the first covering the redshift regime $z \approx 0.5$ from which galaxy groups can be identified in a manner nearly identical to the low-redshift kinematic groups. The CNOC2 groups contain about 20% of $L > 0.2\,L_*$ galaxies. The group galaxy properties are, on average, correlated with the group's velocity dispersion and the position of the galaxies within the group. The galaxies in groups with line-of-sight velocity dispersion (σ_1) above 150 km s^{-1} show a luminosity function and color evolution similar to those of the field galaxy population. The gradient of mean galaxy color in $\sigma_1 > 150$ km s^{-1} groups becomes redder toward the center, indicating a decline in star formation activity. No statistically secure color gradient is present in lower-velocity dispersion groups. The volume rate of merging of group galaxies is estimated using Monte Carlo simulations of the future evolution of each group. Merging is significant, but not population altering, at 2.0% per Gyr per group galaxy at $z \simeq 0.4$. On average, galaxies in groups are dragged inward a factor of 2 in radius over 5 Gyr, with the details depending on radial location and velocity dispersion of the group. The dominant trend from redshift 0.6 to the current epoch is the overall decline of star formation to low redshift, which is common to both group and field (non-group) galaxies. The physical driver of group galaxy evolution is most likely to be gravity, predominantly tidal stripping of halo gas and satellites, with some residual galaxy merging. Given that the pairwise velocity dispersion indicates that the average field galaxy is in a group with $\sigma_1 \simeq 200$ km s^{-1}, this suggests that evolution of field galaxies is driven by the same gravitational processes characterized in our multi-member groups.

1.1 Introduction

Galaxy groups are a much more typical environment for a galaxy to find itself than the relatively rare environment of a rich cluster. The average group in the field, with a line-of-sight velocity dispersion $\sigma_1 \approx 200$ km s^{-1} (e.g., Ramella, Geller, & Huchra 1989; Tucker et al. 2000), is the source of much of the galaxy two-point correlation function and the pairwise velocity dispersion in the field (e.g., Davis & Peebles 1983). At the low-velocity dispersion end of the group range, ~ 100 km s^{-1}, groups of galaxies overlap with the internal velocity dispersions of individual galaxies. At low velocity dispersion and in the dense environment of a group's dark halo, dynamical friction is overwhelming, leading to merging of galaxies

(Barnes 1990; Hickson 1997). In the field, the evolution out to $z \approx 0.5$ is dramatic in the blue galaxies and modest in the red galaxies (e.g., Lin et al. 1999). Evolutionary effects have not been directly examined using a sample that covers a significant range in redshift. Here we first examine the statistics of group evolution, then search for some probable causes.

At low redshift there have been extensive studies of groups and their galaxy contents. The groups have properties, such as numbers, clustering, and mass-to-light ratio, consistent with their being located in dark matter halos (Gott & Turner 1976; Ramella, Geller, & Huchra 1989, 1990; Girardi, Boschin, & da Costa 2000; Girardi & Giuricin 2000). The "light traces mass" aspect is not particularly surprising in 1000 km s^{-1} clusters because dynamical friction on galaxies is slow (Merritt 1985). However, since the dynamical friction time scale varies as σ_1^3, it is much more important in $\sim$200 km s^{-1} groups, as borne out by extensive numerical simulations (for instance, Barnes 1990). At the same time, the effects of ram pressure are proportional to $\rho_{\rm gas}\sigma_1^2$, with $\rho_{\rm gas}$ showing a similar (scaled) density profile with σ_1. Hence, the relative importance of friction relative to gas pressure at a given fraction of the virial radius varies as σ_1^5. Therefore, frictional infall and merging should dominate over ram pressure gas removal in groups. The countervailing gravitational process is tidal stripping, which acts to disrupt infalling smaller groups and remove satellite galaxies. For an approximately universal density profile, tidal effects, which are proportional to the local mass density, are not dependent on group velocity dispersion.

There is substantial observational evidence at low redshift that tides and dynamical friction processes are playing an important role in groups (Toomre 1977; Hickson 1982, 1987). A telling discovery is the "ghost group" (Mulchaey & Zabludoff 1999), in which an isolated elliptical is found within the extended X-ray emission profile that is characteristic of a group of galaxies, rather than of an isolated elliptical. The inference is that the galaxies have merged together to make the elliptical, leaving behind the extended dark matter halo and the X-ray gas. Over the 5 Gyr look-back time of the CNOC2 survey, about half (based on a roughly constant process) of such current-epoch "ghost groups" should be present as small groups, possibly in the process of merging. The rate of merging within the intermediate-redshift groups can be quantified using the observational data and straightforward orbital integrations.

In this paper we first examine the statistical properties of the galaxy population in groups at intermediate redshift. Second, we undertake a Monte Carlo dynamical analysis of the orbital evolution of the group galaxies over a 5 Gyr time span. Both evolutionary studies require a sample selected from a high velocity precision redshift survey; otherwise, projection effects will overwhelm the sample with interlopers. The VIRMOS (Le Fèvre et al. 2001) and DEEP2 (Davis et al. 2001) surveys are now underway and will generate large, new samples, but at the present time the only available survey is the CNOC2 sample (Carlberg et al. 2000; Yee et al. 2000). We note, in passing, that under the assumption of pure luminosity evolution the CNOC2 analysis (Lin et al. 1999) predicts that galaxies like the LMC and SMC will statistically brighten above $M_R = -18.5$ mag at $z \approx 0.5$. Accordingly, the Milky Way at $z \approx 0.5$ would, in principle, be a member of our group catalog, underscoring that these small, intermediate-redshift groups have a substantial connection to the current-epoch field.

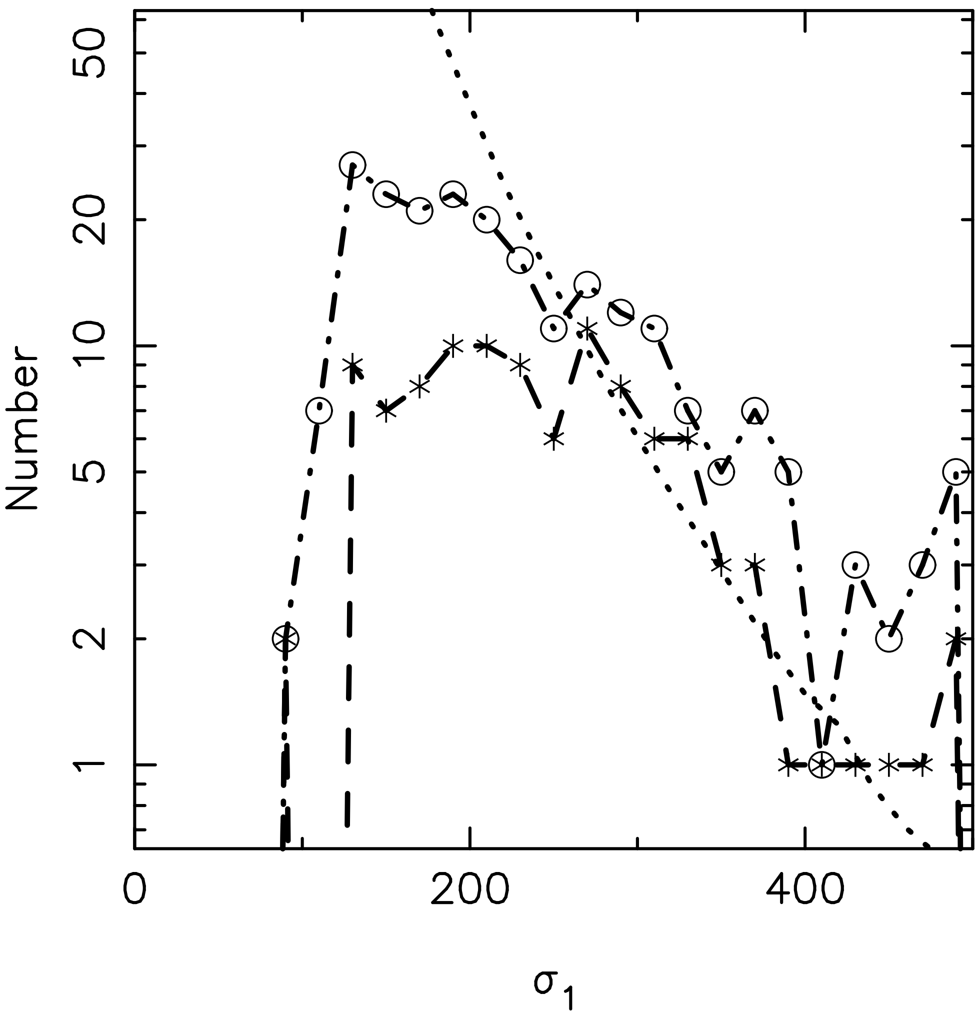

Fig. 1.1. The $n(\sigma_1)$ relation for our standard approach to identifying groups used in our analysis. Both three (upper, solid line) and four member groups (lower, dashed line) are shown. The dotted line is the Press-Schechter prediction. The expected fraction of redshift-space interloper galaxies is only about 15%.

1.2 Properties of the CNOC2 Groups

The CNOC2 redshift survey extends from redshift 0.15 to 0.7, with statistically complete coverage of all galaxy spectral types over the redshift range 0.15 to 0.55. The groups are identified in redshift space using a technique designed to incorporate all galaxies within a virialized halo. The algorithm (Carlberg et al. 2001a) is a redshift-space analog to the algorithm used in N-body simulations to identify virialized dark matter halos by the criterion that the mean interior density exceed 200 times the critical density. Groups are identified as having three or more members within 1.5 times (for $\Omega_m \simeq 0.3$) the radius corresponding to a mean interior density of 200 times the critical density.

Kinematic identification of groups using separation on the sky and along the line of sight using velocities will always be subject to interlopers in velocity space. That is, at velocity separation $\Delta\upsilon$, it is impossible to tell the difference between two galaxies at the same distance with a relative peculiar velocity $\Delta\upsilon$ and two galaxies moving with the Hubble flow separated along the line of sight by a distance $\Delta r_z = \Delta v/H(z)$, where $H(z)$ is the Hubble constant at their redshift. The probability distribution of Δr_z is evaluated using the two-point correlation function with $r_0 \simeq 4h^{-1}$ Mpc (co-moving). The result is that any two galaxies grouped on the sky with separation r_p have a probability of about 50% that $\Delta r_z \leq r_p$. This does not mean that only 50% of the kinematic groups are physical groups. As the number of kinematic group members goes up, so does the probability that the group is a physical group. For two kinematic members it is about 1/2; for three kinematic members the chances that it is at least a physical pair is about 2/3; for four kinematic members the probability of it being a physical group of three is about 3/4, and for it being at least a physical pair is close to 100%, where we use the fact that the three-point correlation function is proportional to the square of the two-point correlation function. In Figure 1.1 we show the groups with at least three and at least four kinematic members over the same range of velocity dispersion. Beyond $\sigma_1 \simeq 150$ km s^{-1}, three-member groups do not dominate the groups, and groups with four and more members comprise $\sim$ 80% of the $\sigma_1 > 200$ km s^{-1} groups, consistent with the analysis of group reality given above. We also note that the numbers as a function of σ_1 are in good correspondence with the Press-Schechter (1974) predictions. The membership status of any particular member of any size group will always have an element of uncertainty that cannot be removed using a redshift survey alone.

1.3 Group Galaxy Evolution

Group galaxies show evolution trends similar, but not entirely identical, to those of field galaxies. We divide galaxies by color at a k-corrected $(B-R)_0$ = 1.25 mag. The red galaxies have essentially identical luminosity function evolution in the group and the field, as shown in Figure 1.2. The modest evolution of the red galaxies is well known to be consistent with passive evolution alone.

The evolution of the blue galaxy luminosity function in groups (Fig. 1.3) has an additional twist relative to the red galaxies. The luminosity function of galaxies in high-velocity dispersion groups evolves in a manner similar to the field. In both groups and the field the evolution is very strong, approximately half a magnitude in luminosity over a redshift interval of only $\Delta z = 0.16$. On the other hand, the low-velocity dispersion groups show effectively no luminosity function evolution.

The similarity of evolution in the field and groups has two possible causes. One possible explanation is that both sets of galaxies share the same cosmic clock and are genuinely evolving in parallel due to a universal driver common to both. A physical cause would be the expansion of the Universe and the decline in density of gas and galaxies. The other possible explanation is that the conditions in groups cause group galaxies to evolve, and that since all galaxies are statistically known to be in a virialized group of some sort, on the basis of the correlation function and extending the group definition to include low-luminosity galaxies, then galaxy evolution *is* group galaxy evolution.

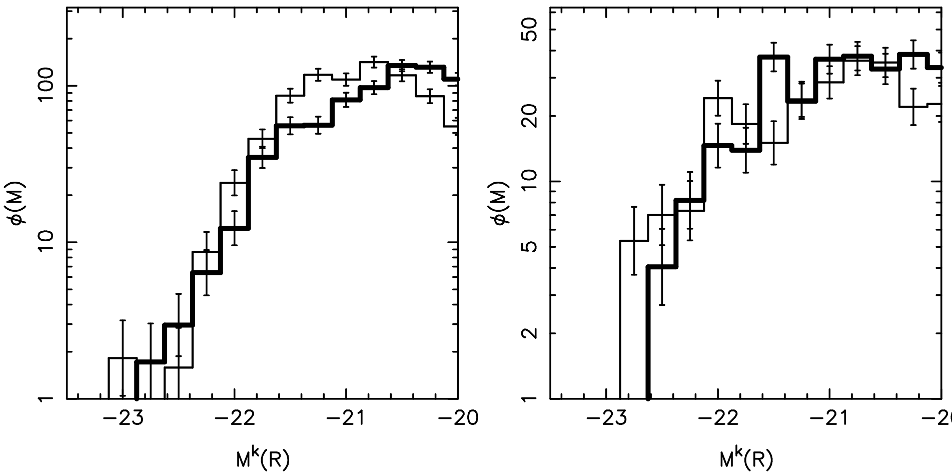

Fig. 1.2. The luminosity functions of red galaxies, $(B-R)_0 > 1.25$ mag, in the field (*left*) and in groups (*right*), for galaxies at a mean redshift of 0.27 (thick line) and 0.43 (thin line). No significant evolution is present.

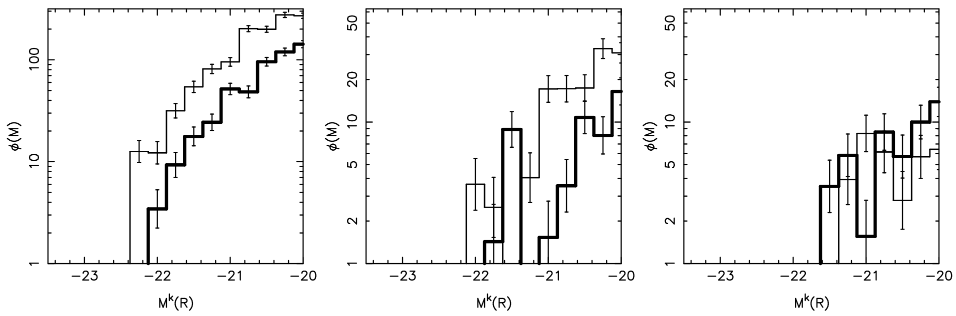

Fig. 1.3. The luminosity functions of blue galaxies, $(B-R)_0 < 1.25$ mag, in the field (*left*) and in groups above (*middle*) and below (*right*) σ_1 = 150 km s^{-1} at a mean redshift of 0.27 (thick line) and 0.43 (thin line).

1.4 Radial Color Gradients of Groups

Groups show a significant radial color gradient, with galaxies being statistically redder the closer they are to the center, as shown in Figure 1.4. The color gradient is naturally interpreted as a variation in star formation rate. The star formation gradient interpretation is supported directly with unpublished $U-I$ colors and [O II] line-strength measurements. A similar result holds at low redshift (Hashimoto et al. 1998).

The existence of a color gradient in groups indicates that the group galaxy properties are correlated with their group environment. A key question is what is the physical origin of the group color gradient. There is a reasonably clear idea of how groups build up with time. Any dark halo is, on average, subject to ongoing infall from surrounding field galaxies. Infall causes the object to increase in mass and size, with the new galaxies being added at the periphery. Therefore, as one moves from the center outward through the group the galax-

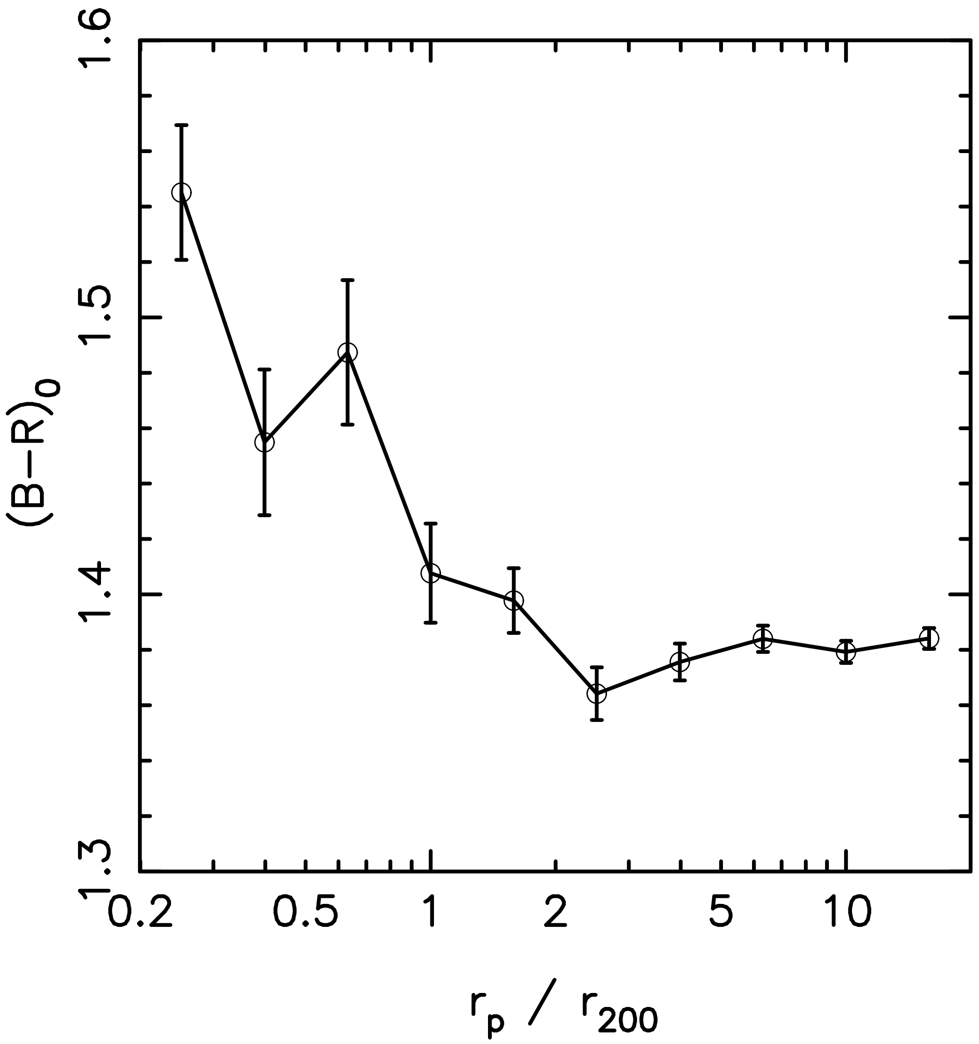

Fig. 1.4. The gradient of color across the groups with a velocity dispersion greater than 150 km s^{-1}. Mergers are expected to be rare in this subsample, although the galaxies are drawn inward by dynamical friction by about a factor of 2 in their orbits over the 5 Gyr time interval between today and the sample's redshift. This net inward flow demands some transformation of the galaxies, not purely an initial distribution.

ies become, on average, progressively more recent additions to the group. In the case of small groups having only three or four members the "time of entry" gradient is substantially blurred by orbital motions. In spite of that, the relatively red colors of the central galaxies have two possible explanations: either they had some internal clock that indicated at formation that they would become red, or they were average field galaxies that the environment of the group forced to become redder.

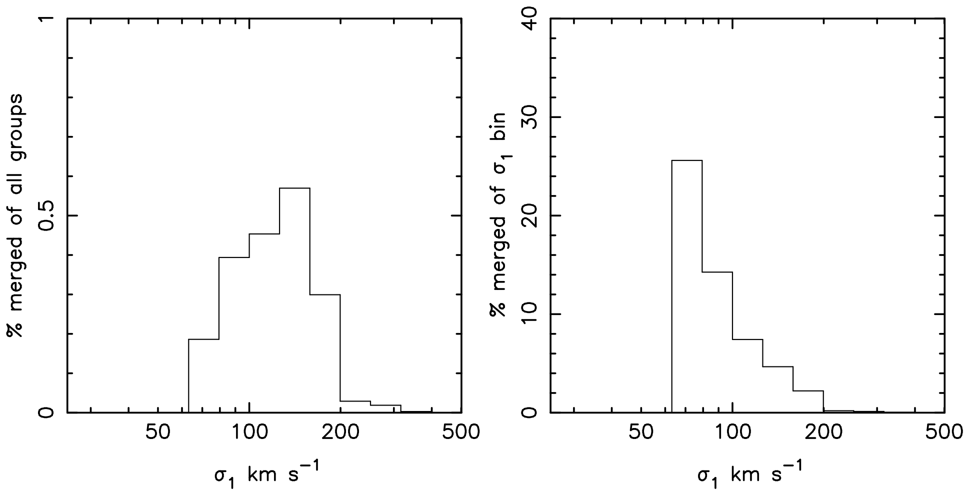

Fig. 1.5. (*Left*) The fraction of the whole sample that is merged in each bin of velocity dispersion in 1 Gyr. The integrated rate is 2.0% per Gyr per group galaxy. (*Right*) The percentage of galaxies in groups of σ_1 merged per Gyr.

1.5 Merging and the Inward Flow of Group Galaxies

The importance of merging of group galaxies is estimated using Monte Carlo integrations of each galaxy in its group. The median line-of-sight velocity dispersion of the CNOC2 groups, 230 km s^{-1}, is close to the velocity dispersion above which dynamical friction in a cosmological dark halo is no longer able to drag any galaxies down to the center in a Hubble time. The calculations use the measured (x, y, v_z) of every galaxy and distribute the galaxies over (z, v_x, v_y) using the measured statistical distribution in r_p and line-of-sight velocity dispersion σ, assuming an isotropic velocity ellipsoid. The dark halo is modeled as an isothermal sphere. Any orbit that comes within 0.03 units of the center is assumed to merge into a central galaxy. Some of the resulting starting points have orbits unbound from the cluster; these were removed from the analysis.

The left panel of Figure 1.5 shows the fraction of all group galaxies that merge in 1 Gyr as a function of the group velocity dispersion. The rate is calculated on a galaxy-by-galaxy basis using the observed positions and velocities of the group galaxies. At a fixed velocity dispersion, the merger rate is proportional to σ_1^{-3}, as expected, as shown in the right panel of Figure 1.5, where the fractions are normalized to the numbers in the bins.

The group catalog is constructed using all galaxies down to about $0.2L_*$ and does not include any low-mass galaxies. Given the relatively limited range of masses, the mean mass of galaxies merging is essentially equal to the mean mass of all galaxies in the group sample. The merger rate integrated over all groups is a mean rate of mass increase of 2.0% per Gyr. Although this rate is nontrivial, it is not sufficient to lead to gross changes in the galaxy population between redshift of 0.5 and the current epoch. The merging will lead to a small population of recent major-merger galaxies at the current epoch, 2.0% per Gyr, for 5 Gyr, equal to 21% of galaxies in groups or 2% of all galaxies. The merger rate is low enough that it presents no serious threat to the existence of the group population. At higher redshift the mass density within the virialized groups rises in proportion to $H^2(z) \sim (1+z)^{2-3}$, leading to

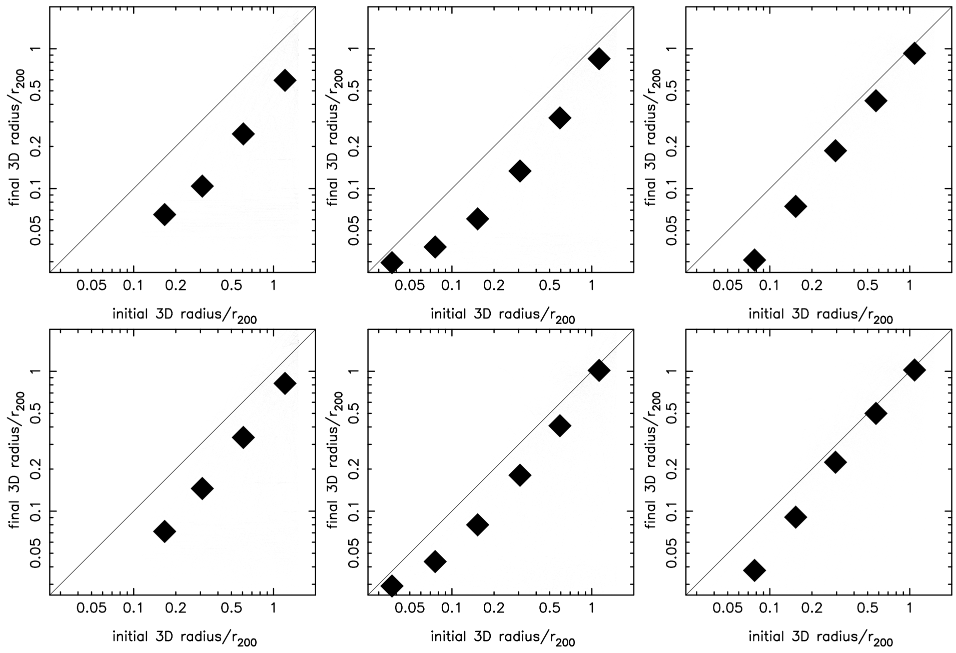

Fig. 1.6. The three-dimensional radial distance from the center after 5 Gyr or at time of central merger plotted against the initial projected radius for galaxies in groups with $\sigma_1 < 150$ km s^{-1} (*left*), 150 km s^{-1} $< \sigma_1 < 250$ km s^{-1} (*middle*) and $\sigma_1 > 250$ km s^{-1} (*right*). The top row uses $M/L = 100$, and the bottom uses $M/L = 30$. The diamonds show the mean final radius for the galaxies at that range of initial radius.

a rise in the importance of merging with redshift. The density effect accounts for a rise in the group merger rate of roughly $\sqrt{\rho} \sim (t_0/t) \sim (1+z)^{1-1.5}$.

Dynamical friction causes the orbits of the group galaxies to spiral inward, sometimes fairly quickly. In the presence of a radial inflow a color gradient will be reduced, possibly to no gradient at all, as a result of blue galaxies moving inward. If the gradient remains present, then the group environment is acting to suppress star formation as blue, star-forming galaxies enter the group.

The same calculations that predict the merger rate also follow the individual galaxy orbits. We display the final orbital radius as a function of initial orbital radius in Figure 1.6. Also shown is the average final radius as a function of initial radius. Within our sample of group galaxies as a whole, the average galaxy moves inward by about a factor of 2 in radius. The figure shows that the details depend on group velocity dispersion and initial galaxy radius, with a fairly weak dependence on the assumed total M/L for the galaxies plus their remnant dark matter halos. The expected trends of an increased inward drift with lower velocity dispersion and smaller initial orbital radius appear, although it is diluted by the projection effects that spread galaxies out of the groups along the line of sight and give some galaxies relatively large tangential velocities.

On the basis of these integrations we have found that there is substantial radial inspiral of group galaxies. The radial inflow in systems with $\sigma_1 < 150$ km s^{-1} is likely to be so rapid that it can explain the absence of any secure color gradient in these groups, and possibly an excess of strongly star-forming galaxies at the center (Hashimoto & Oemler 2000; Carlberg et al. 2001b). The color gradient is present in groups at 150 km s^{-1} $< \sigma_1 <$ 250 km s^{-1}, where the net radial inflow is about a factor of 2 in radius. A reasonable interpretation is that the presence of galaxies redder than the field toward the centers of groups is largely due to the influence of the group environment. One important force in groups is simply the tidal effect of the group, which can gravitationally strip off halo gas and smaller, gas-rich companion galaxies that infalling galaxies bring with them as they fall into the group (or equally, cluster).

1.6 Consequences of Galaxy Evolution in Groups

At intermediate redshift, group galaxies evolve parallel to galaxies in the field. Given that groups comprise about 21% of the field, if we include galaxies with luminosities greater than $0.2L_*$, and would rise if we include lower-luminosity galaxies, at least some of the cause of the evolution of galaxies in the field is that they are in a group environment and have their star formation rates reduced as they move toward the centers of groups.

Low-velocity dispersion groups are where mergers occur. Low-velocity groups are under-represented relative to the Press-Schechter prediction in our sample. At higher redshift the importance of mergers will be much greater because dark halo densities rise, and it is likely that groups are the primary source of major mergers.

At much earlier epochs, say redshifts beyond about 2, we can speculate that the role of groups will change. At low redshift their dominant role appears to be to suppress star formation activity. At higher redshifts there will be relatively fewer groups with $\sigma_1 > 150$ km s^{-1}, and the mean mass density will rise in proportion to the local Hubble constant, $\rho_{200} \propto H^2(z)$. Hence, dynamical friction and merging are bound to be much more important than at low redshift. Furthermore, it is likely that the galaxies are much more gas rich. Consequently one expects that there will be increased merger activity, almost certainly with increased induced star formation. The task of extending a redshift survey with $\sim 10^5$ galaxies to redshifts in the range 2 to 5 is an observational challenge required to develop an understanding of the links between structure in the dark matter and the formation of galaxies.

1.7 Conclusions

The groups at intermediate redshift are the galaxy population that creates much of the clustering signal measured in the two-point correlation function and pairwise velocities. These groups have the following properties.

- The luminosity function of both blue and red galaxies in groups with velocity dispersion $\sigma_1 >$150 km s^{-1} evolves like field galaxies.
- The $\sigma_1 > 150$ km s^{-1} groups have internal color gradient, becoming redder toward the center.
- The rate of mass increase due to merging of group galaxies is 2.0% per Gyr.
- On average, dynamical friction will drag group galaxies inward about a factor of 2 in 5 Gyr.
- We speculate that the gravitational forces that cause a decline in star formation in group galaxies as they move inward is also a significant driver of the evolution of the field as a whole, on the basis that the average galaxy is in a $\sim$ 200 km s^{-1} group.

The CNOC2 groups will statistically evolve over an average of about 5 Gyr into most of the group galaxies seen today. Based on the merger rate in groups, the mean mass of galaxies will increase only about 2% due to group merging; approximately half of those will become single galaxies. On the other hand, the tendency of galaxies to become redder as they move toward the group center will affect virtually all group galaxies and is at least partially responsible for the decline in star formation between redshift 1 and 0.

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