ENVIRONMENTALLY DRIVEN EVOLUTION OF SIMULATED CLUSTER GALAXIES

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ABSTRACT

Galaxies in clusters are gas deficient, and a number of possible explanations for this observation have been advanced, including galaxy–cluster tidal interactions, galaxy harassment, and ISM-ICM gas stripping. In this paper, we use a cosmological simulation of cluster formation and evolution in order to examine this issue from a theoretical standpoint. We follow a large number of galaxies over time and track each galaxy’s gas and stellar mass changes to discover what mechanism(s) dominate the evolution of the cluster galaxies. We find that while gas is lost due to a wide variety of mechanisms, the most common way is via a gas-only stripping event, and the amount of gas lost correlates with the ram pressure the galaxy is experiencing. Although this gas stripping occurs primarily in the central region ($r < 1$ Mpc), it is an important mechanism out to the virial radius of the cluster. This is due to the wide scatter in ram pressure strength that a galaxy experiences at fixed radius. We find that the timescale for complete gas removal is $\geq 1$ Gyr. In addition, we find that galaxies in the field and in the cluster periphery ($r > 2.4$ Mpc) often accrete cool gas; the accretion stops between 1 and 2.4 Mpc, possibly indicating the onset of galaxy starvation.

Subject headings: galaxies: clusters: general — galaxies: interactions — methods: $n$-body simulations

Online material: color figures

1. INTRODUCTION

It has long been known that a galaxy’s environment has an impact on its morphology: spirals dominate in the field, and ellipticals and S0s are more prevalent in dense cluster environments (Hubble & Humason 1931). This has been quantified in the density-morphology relation (Oemler 1974; Dressler 1980), but this relation alone does not determine whether the cluster environment affects the formation or the evolution of galaxies. According to the Butcher-Oemler effect, cluster galaxies at $z \geq 0.2$ are bluer than nearby clusters (Butcher & Oemler 1978), indicating that cluster age or evolutionary status may be related to the evolution of galaxies from spirals to earlier types. It has been found that the spiral to S0 ratio increases with decreasing redshift (Dressler et al. 1997; Fasano et al. 2000). More recently, by examining a specific merging cluster, Tran et al. (2005) presented a strong relationship between the Butcher-Oemler effect and infalling galaxies.

More generally it is found that galaxies evolve both morphologically and spectroscopically, where the fraction of early-type galaxies and non-star-forming galaxies increase with time at a rate that depends on the local density (Smith et al. 2005; Postman et al. 2005; Poggianti et al. 1999; Dressler et al. 1997). The timescale for the transformation differs for the two processes. Spectroscopic transformation precedes morphological transformation (Dressler et al. 1997; Poggianti et al. 1999).

A wide variety of physical processes may be responsible for these evolutionary trends. Galaxy–intercluster medium (ICM) interactions are ones in which the gas in a galaxy interacts with the ambient intercluster hot gas. One such process is ram pressure stripping (RPS), which removes the interstellar medium (ISM) of a galaxy as it moves through the ICM (Gunn & Gott 1972); ram pressure could also compress the gas within a galaxy to cause a burst of star formation that would consume gas that has not been stripped (Fujita & Nagashima 1999). An ISM-ICM interaction is the only type of interaction that does not affect the stellar component of a galaxy. Starvation, the removal of the outer gas envelope by the ICM, can result in normal star formation slowly exhausting the gas reservoir in the central region of the galaxy (Larson et al. 1980). A galaxy can also interact with the cluster potential, which can strip both gas and stars, or compress the gas to cause an increased star formation rate (Byrd & Valtonen 1990). These galaxy-cluster interactions affect both the stellar and gas components of galaxies. There are also possible galaxy-galaxy interactions that can take place within a cluster. These include mergers between galaxies with low relative velocities, as well as galaxy harassment—high-speed interactions between cluster galaxies (Hashimoto et al. 1998; Bekki 1998, 1999; Barnes & Hernquist 1991; Moore et al. 1996). These interactions can cause an increased star formation rate and will also affect both the stellar and gas components of galaxies.

It is likely that all of these processes occur in clusters. Attempts to differentiate the relative importance of these effects have been widespread through the years. For example, Bahcall (1977) showed that X-ray luminosity is positively correlated with the S0/spiral ratio in clusters (Bahcall 1977), and that the ratio of spirals to S0s increases radially (Melnick & Sargent 1977). Observational studies of H i deficiency have shown that spirals in clusters have less neutral atomic hydrogen than galaxies of the same morphological type in the field (see the reviews by Haynes et al. 1984). On the other hand, the CO content does not seem to depend on environment (Stark et al. 1986; Kenney & Young 1989). H i imaging of spirals in the center of Virgo shows smaller H i disks than stellar disks, pointing to an ISM-ICM interaction (Cayatte et al. 1990; Warmels 1988). More recently Koopmann & Kenney (2004) have shown that in Virgo the reduced massive star formation rate is primarily caused by truncation of the star-forming disks; thus, it is the removal of the lower density atomic gas that seems to control the star formation rate. Solanes et al. (2001) studied H i deficiency in a sample of 18 cluster regions, and found that H i deficiency decreases smoothly out to large projected distances from cluster centers. In a recent H i imaging study of Virgo, Chung et al. (2007) find a number of long one-sided H i tails pointing away from the cluster center. These galaxies are likely falling in for...
the first time, and gas is indeed already being removed at large projected distances from the cluster center.

Others have combined simple analytic models with cluster galaxy observations to determine the evolutionary mechanism at work. For example, Treu et al. (2003, hereafter T03) use a large wide-field mosaic of HST images in combination with a simple cluster model to identify the operating environmental process. They find that galaxy star formation rate and morphological type have mild gradients outside of the central megaparsec of the cluster. This leads them to conclude that only slow (>1 Gyr) processes that can affect galaxies in the outer regions of clusters could be responsible, and therefore that galaxy starvation and harassment are the most likely mechanisms that evolve cluster galaxies. In addition, detailed investigations of a few individual galaxies using multiple wavelengths have begun to unravel their probable histories (e.g., Crowl et al. 2005; Chung et al. 2005). Observations of NGC 4522 indicate that the galaxy is undergoing RPS, although it is outside of the high-density ICM (Kenney et al. 2004). Clearly, these varied results show the complicated nature of galaxy evolution in clusters.

The limitation of all observations is that they are snapshots of a long process, and cannot make detailed conclusions about both the history and fate of individual galaxies. To overcome this limitation, simulations are now being used to inform the debate about which morphology-changing mechanism is operating by modeling previously observed galaxies (e.g., Vollmer et al. 2005). For example, Vollmer (2003) shows that one Virgo Cluster galaxy in particular has both undergone RPS and been involved in a gravitational interaction. Others have studied idealized cases of galaxies in clusters (e.g., Quilis et al. 2000; Roediger & Brüggen 2006).

In this paper, we take a different approach and use a cosmological hydrodynamics simulation in order to track the evolution of a large number of galaxies in the close vicinity of a large galaxy cluster. The simulation is performed in a cosmological context and includes dark matter, gas dynamics, and a treatment of star formation (see § 2.1). In this way, we can study the environmental impact of the intracluster gas, the cluster potential, as well as other galaxies in a self-consistent fashion. Although we have insufficient resolution to determine the morphological type of our galaxies with confidence, we can compare the gas content of our simulated galaxies directly to observations.

The advantage of using a cosmological simulation is that we do not need to guess the specific environmental conditions of our galaxies; instead, the local environment is naturally modeled by the simulation. This might be important if, for example, the intracluster medium has internal motions that increase the efficiency of RPS above that expected in a static medium, or if galaxies preferentially enter the cluster in groups. The output from this simulation can tell us about the evolution of a particular galaxy and give an overview of what mechanisms are at work in a cluster environment. In this paper we concentrate on the latter by following the changing gas and stellar mass of 132 galaxies in our cluster. In particular, we focus on the period after the cluster has been established and ask how the gas content of infalling galaxies changes. Our data tell us how the gas content of gas-rich galaxies is affected by the cluster, an important part of the evolution of spiral galaxies to earlier types.

This paper is organized in the following way. After a brief introduction to our code, we provide a comparison of the general characteristics of our simulation to current observations (§ 2.1). We then explain the construction of our sample of galaxies and simulated “observations” (§ 2.2). In § 3 we describe our results and present an analysis of the importance of the various gas removal mechanisms in our simulation. We conclude (§ 4) with a discussion of the limitations and implications of our results.

2. METHODOLOGY

2.1. Simulation

We have simulated a massive cluster of galaxies with the adaptive mesh refinement (AMR) code Enzo. This cosmological hydrodynamics code uses particles to evolve the dark matter and stellar components, while using an adaptive mesh for solving the fluid equations including gravity (Bryan 1999; Norman & Bryan 1999; O’Shea et al. 2004). The code begins with a fixed, static grid and automatically adds refined grids as required in order to resolve important features in the flow (as defined by enhanced density).

The cluster forms within a periodic simulation box that is 64 h⁻¹ Mpc on a side, in a flat, cosmological-constant-dominated universe with the following parameters: \((\Omega_0, \Omega_{\Lambda}, \Omega_b, h, \sigma_8) = (0.3, 0.7, 0.045, 0.7, 0.9)\). We employ a multimass initialization technique in order to provide high resolution in the region surrounding the cluster, while evolving the rest of the box at low resolution. Time steps are also refined in the more dense regions to follow in detail the rapidly changing conditions. The dark matter particle mass is \(6.4 \times 10^8 M_\odot\), with a gas mass resolution about 5 times better than this. The whole cluster has about 1 million dark matter particles within the virial radius, and a typical \(L_v\) galaxy is resolved by several thousand dark matter particles. The AMR provides higher resolution in high-density regions, giving a best cell size (resolution) of 3 kpc. This is sufficient to resolve the large galaxies in which we are interested, and also, we believe, to approximately reproduce effects such as RPS (although it is clear that the internal dynamics of galaxies will not be well resolved). A study of the gas-stripping properties of this code is presented in Agertz et al. (2007), which demonstrates that the resolution required to correctly reproduce stripping in grid-based codes is less stringent than in particle-based codes. We discuss our tests of different resolutions in greater detail in the Appendix.

In Figure 1 we show a snapshot of the gas and stellar distribution in our cluster. This shows two features: the first is that most stellar systems within the cluster show only a stellar component, and the second is several clear cases of gas being stripped from galaxies. These can be seen by the associated tail, which often points away from the cluster center.

The simulation includes radiative cooling using the Sarazin & White (1987) cooling curve, and an approximate form of star formation and supernovae (SNe) feedback following the Cen & Ostriker (1992) model. Briefly, the star formation method relies on identifying cold, collapsing, high-density clouds and forms stars at a rate proportional to the density of gas divided by the dynamical time, multiplied by an efficiency factor. This efficiency is taken to be, somewhat arbitrarily, 2%. See O’Shea et al. (2004) for a more complete discussion of the star formation algorithm. Stars are represented as stellar particles, and the energy from Type II SNe is returned to the gas in the form of thermal energy. Although this energetic output can be important, it is known that much of this energy is deposited in high-density gas where the cooling time is short and so is radiated away. This results in an “overcooling” problem (e.g., Balogh 2001), and manifests itself in our simulations as somewhat overly massive galaxies, as well as a higher than observed ratio of stars and cool gas to hot gas. In addition, we observe hot intracluster gas cooling onto the centers of a few of the most massive galaxies (and in particular the central galaxy). This cooling is not observed in real clusters, probably...
because of feedback from supermassive black holes, which are not included in the simulation.

2.2. Construction of the Sample

Although our simulation runs from $z = 40$, we only wish to compare our results to nearby, virialized galaxy clusters, and thus only consider our simulated cluster from $z = 0.352$ to the present.\(^1\) We output information from the simulation at time intervals of approximately 0.122 Gyr (although the time steps within the simulation are orders of magnitude smaller), for a total of 33 output times. The output includes (1) the position, mass, size, creation time, and metallicity of each star particle; and (2) the position, mass, cell size, temperature, metallicity, and velocity of each gas cell.

In the construction of our sample, we first separate our star particles into distinct galaxies based on regions of high density in our $N$-body stellar code. A visual inspection of the data shows that (as in real clusters), galaxies are easy to identify because they are highly concentrated, with relatively few stars between galaxies. This is unlike the case for dark matter substructure, where it can often be quite difficult to associate a given dark matter particle with a given subhalo. We used the HOP algorithm (Eisenstein & Hut 1998), which uses a two-step procedure to identify individual galaxies. First, it assigns a density to each star particle based on the distribution of the surrounding particles and then hops from a particle to its densest nearby neighbor until a maximum is reached. All particles (with densities above a minimum threshold, $\delta_{\text{outer}}$) that reach the same maximum are identified as one coherent group. In the second step, groups are combined if the density at the saddle point that connects them is greater than $\delta_{\text{saddle}}$. We chose HOP because of its physical basis, although we expect similar results would be found using a friends-of-friends halo finder. We set $\delta_{\text{outer}}$, the minimum density for a particle to be part of a group, to 10,000; $\delta_{\text{peak}}$, the minimum central density for a galaxy, to 30,000; and $\delta_{\text{saddle}}$, the boundary density needed to merge two groups, to 25,000 (all density values are relative to the cosmic mean). We chose these values because by visual examination we found that they picked out a single galaxy as the central object; however, reasonable variations in these parameters did not make a significant difference in the number of galaxies. Using this algorithm, we find that each output (from $z = 0.35$ until $z = 0$) has between 155 and 186 galaxies within a $12^3$ Mpc$^3$ box.

HOP separates the cluster into a set of galaxies at each output, but we still need to identify and follow a set of individual galaxies as they move through the cluster with time. We expect that the particles with the highest density correspond to the most central particles in a galaxy. Therefore, we first used the density for each star particle as calculated by HOP to select the 150 densest particles in every galaxy in every output (using the 80 densest particles produced similar results). For any galaxy with less than 150 particles we used the entire set. Then, starting with each galaxy in our first output, we looked through the sets of densest star particles in all of the galaxies in the next output for a match between particle identification numbers (which indicates the same star particle at the center of both galaxies). If there were one or more matches between galaxies in consecutive times, we concluded that we were following a single galaxy. We continued this process from one output to the next for all 33 times.

Because we intend to compare our results to observations of nearby virialized clusters, we only follow galaxies that were in our box from $z = 0.35$ until $z = 0$. There were 155 galaxies in our earliest output, which dictated the maximum number of galaxies we could follow. Any galaxy that had no match from one output to the next was dropped from our sample. If a galaxy was dropped at any time, no part of its evolution is reported in the statistical results given below. Of the 155 galaxies with which we began, we were able to track 133. Because one of these is the cD galaxy, we report on the evolution of 132 galaxies. Ten of these galaxies merged before $z = 0$, so by the end of our simulation we report on 126 individual galaxies. It is notable that although we can track arbitrarily small galaxies, none of the galaxies on which we report ever have less than 150 stellar particles. In fact, 64 of the galaxies we follow always have at least 3000 particles, and using only those galaxies in the following analysis gives similar results.

\(^1\) Visualizations of these simulations can be found at http://www.astro.columbia.edu/~gbryan/ClusterMovies.
Our galaxies were dropped for a number of possible reasons. They may have been swallowed by the cD, ripped apart by either the cluster potential or galaxy harassment, or merged into a galaxy that we did not follow. Also, a galaxy was dropped if it left the box. HOP may erroneously group two distinct galaxies together during a close flyby, and we dropped a galaxy if it was grouped with one that we did not follow. By examining our data on the galaxies before they were dropped, we found lower limits for three of our dropping mechanisms: four galaxies left the box, and four galaxies were swallowed by the cD, while three galaxies were incorrectly grouped by HOP (out of a total of 22 dropped galaxies).

2.3. Galaxy Definition

By following these 132 galaxies, we are able to determine both how many galaxies in a cluster underwent environmentally driven evolution as well as the mechanisms that were driving their evolution. To do this, we measured the gas mass and stellar mass of each galaxy through time, using any changes to identify the mechanisms at work. The mechanisms we consider fall into three broad categories: ISM-ICM, galaxy-galaxy, and galaxy-cluster. For example, an ISM-ICM interaction would not change the stellar mass of a galaxy, but would reduce the gas mass. A galaxy-galaxy or galaxy-cluster interaction would affect both the gas mass and stellar mass, and depending on whether the masses increased or decreased, we would label the acting mechanism either tidal accretion or stripping.

Because our determination of the environmental mechanism at work depends solely on the mass evolution of a galaxy, we examined our data in detail to carefully define the boundaries of each galaxy. Although we were able to use HOP to find our galaxies, locate their centers (defined as their points of maximum density), and track them through time, actually using HOP to determine the stellar mass led to substantial fluctuations in their estimated masses. To minimize this sort of noise, we defined our galaxies' masses to include all the stars and cool gas ($T \leq 15,000$ K) within a sphere of a uniform radius. We originally chose the largest radius as defined by HOP (90 kpc) and applied it to all galaxies, but found that this introduced unphysical fluctuations in both the stellar and gas mass because it tended to combine distinct galaxies that happened to have overlapping radii. Therefore, we examined the radial density profiles, and found that a radius of 26.7 kpc almost never included gas from nearby galaxies, while by this radius the gas densities had usually gone to zero. All but four galaxies were sufficiently compact that the 26.7 kpc radius included 80% or more of the mass within the larger 90 kpc sphere.

3. RESULTS

3.1. Gasless Galaxy Distribution

We first compare the morphology distribution in the simulation and observations. Because the internal structure of our galaxies is not well resolved, we adopt a different classification scheme than traditional morphological type. Instead, we relied on the amount of gas mass, dividing them into two types: those with and those without cool gas ($T \leq 15,000$ K). We cannot comment on the molecular gas in the simulated galaxies because gas in our simulation cannot radiatively cool to molecular cloud temperatures, and long before it collapsed to the density of molecular clouds it will have formed stars. Therefore, we do not comment on molecular gas throughout this paper, although we do expect that it might be stripped more slowly than the lower density gas that we do follow.

While this classification scheme is overly simplified, it is still instructive to consider the resulting distribution. For example, the 132 galaxies that we track through time show a clear cluster radius and gas content relation, seen in Table 1. Gasless galaxies begin to dominate the population at 2 Mpc, and galaxies with gas dominate at large radii and outside the cluster. We considered our output for the 132 galaxies at 15 equally spaced ($\approx 0.244$ Gyr) output times, thus giving us 1980 observations. We treat each data point as distinct because, although every galaxy is measured 15 times, at each observation it is in a different part of the cluster and therefore could be influenced by different environmental effects. This is less true for galaxies far from the cluster center.

Ideally, we would compare our galaxies to observations of the galaxy gas population; however, large, complete samples extending to large radius do not yet exist. Although our gasless galaxies could be either E+S0s or spirals, we expect the majority of our gasless population to be E+S0s. If we make this rough translation, we can compare our galaxy distribution to the observations of T03. We choose this comparison because our simulated cluster has a virial radius (calculated as $r_{200}$) similar to that of Cl 0024+16 (1.8 and 1.7 Mpc, respectively), and we can split our cluster into the same diagnostic regions as in T03: 0–1 Mpc is the central region; 1–2.4 Mpc is the transition region; and 2.4–5 Mpc, the periphery. However, our simulation differs from observations in that we have the exact distance from cluster center of all our galaxies in three dimensions, so we do not have any uncertainty due to projection effects.

In our simulation, gasless galaxies dominate the population within 200 kpc, comprising 93.5% of the galaxies. We compare our gasless fraction to the E+S0 fraction reported by T03 in Table 1. Within 1 Mpc, our gasless galaxy fraction is larger than the E+S0 fraction of T03. Between 1 and 2.4 Mpc the fraction of gasless galaxies in our simulation is within 1 $\sigma$ of the observed E+S0 fraction. In the outer region (2.4–5 Mpc) the gasless galaxy fraction is less than half of the fraction of E+S0 galaxies observed in the field.

While this qualitative agreement is promising, we can speculate about the cause of the observed disagreement. If our simulated cluster were older than that observed by T03, we would expect our elliptical fraction in the central regions to be larger than the value they find (T03 and references therein). Also, our gasless fraction may be high because we have no dilution of our central region sample due to projection effects.
However, one of the most important reasons for the mismatch between our gasless galaxy distribution and T03’s E+S0s is that we are comparing two different populations and assuming there is significant overlap. Because we are counting gasless galaxies instead of E+S0 galaxies, any gasless spirals in the inner regions of our cluster will cause our fraction to be higher than T03’s. For example, Solanes et al. (2001) have observed highly deficient spirals in the central regions of clusters. Also, E+S0s are not necessarily gasless in the field (Morganti et al. 2006 and references therein).

In the outer regions, the overabundance of cool gas is consistent with previous simulations of galaxy formation, a problem often referred to as the overcooling problem. One suggested solution to this problem is energetic feedback from active galactic nuclei (AGNs), which can heat up cool gas and eject it from the galaxy (e.g., Bower et al. 2006). Therefore, we caution that we may be overestimating the number of galaxies with gas and the amount of cool gas some galaxies contain.

In addition to the overcooling problem in elliptical galaxies in general, one or two of the galaxies in the central regions of our cluster have a very large amount of cool gas ($>10^{13} M_\odot$). As noted above, the lack of AGN feedback in our simulations is one possible reason for these high gas masses. Indeed, half of the observations of galaxies with gas mass over $10^{13} M_\odot$ are of the largest galaxy we follow at different times. This galaxy may be large enough that it is susceptible to the same overcooling problem as the cD galaxy.

### 3.2. Simulated Galaxy Evolution as a Function of Environment

We will now use our simulated sample to examine how a galaxy gains and loses mass. Recall that we track the evolution of galaxies purely by following the changing gas and stellar mass of each galaxy. Using only the change in stellar mass and gas mass, we have five likely evolutionary tracks: (1) gas mass loss without stellar mass loss, indicative of an ISM-ICM interaction; (2) gas mass gain without stellar mass gain, suggesting gas accretion; (3) gas mass loss equal to stellar mass increase, implying star formation; (4) both gas and stellar mass loss, indicative of tidal stripping or galaxy harassment; and (5) increase in both gas and stellar mass, suggesting accretion or a merger. Each of these processes is represented by a unique vector in the $(\Delta M_{\text{gas}}, \Delta M_{\text{star}})$ plane, which is shown in Figure 2.

From our simulated data we can compute the change in gas and stellar mass for each galaxy during each time step $(\Delta M_{\text{gas}}, \Delta M_{\text{star}})$ and plot this value for each galaxy for each time step in Figure 2. Out of a total of 1980 points, we only show the galaxies that may be affected by the cluster environment, defined as being closer than 5 Mpc to the cD during each 0.244 Gyr time step. This leaves us with 1257 observations of cluster galaxies. To make most of the points in our plot more readable we have zoomed in.

![Figure 2](image-url)
on the inner region of our graph. Thus, two of the merger observations are outside of the range of this plot, and a few observations along the y-axis. Fewer than 2% of our observations are outside of the plot range in Figure 2.

Star formation may or may not be environmentally induced, so in this initial examination of galaxy evolution, we remove its effect on the gas and stellar mass. To do this, we first used the creation time of every star particle in our code to identify the amount of stellar mass formed during a time step. We then transferred all of a galaxy’s stellar mass that was created during that time step to the gas mass of that galaxy. Thus, when we plot a galaxy that had only undergone star formation during a time step in this figure, we will see no change in either the stellar or gas mass. This process is done separately for each galaxy and each time step.

Our results are shown in Figure 2, with a more quantitative view of the results in Table 2. In the table, for all nine possible categories, the total change in gas mass summed over all observations, and (3) the total stellar mass change. The total mass changes are in units of $10^{10} M_\odot$. There are a total of 1257 observations.

| TABLE 2 |
| --- |
| CHANGES TO GAS AND STELLAR MASS |
| OF GALAXIES OBSERVED |
| WITHIN 5 Mpc OF THE cD |
| Gas Mass Loss | Constant Stellar Mass Accretion | Gas Mass Loss |
| 5 | 57 | 26 |
| $-6.747$ | $-0.57$ | $56.991$ |
| $4.267$ | $49.254$ | $62.578$ |
| Stellar Mass Accretion |
| 84 | 729 | 169 |
| $-65.834$ | $6.977$ | $158.785$ |
| $-5.893$ | $-27.433$ | $-4.349$ |
| Stellar Mass Loss |
| 18 | 125 | 44 |
| $-14.83$ | $-0.312$ | $54.597$ |
| $-120.412$ | $-220.414$ | $-85.618$ |

**Notes.**—This charts the possible changes to gas and stellar mass of the galaxies that are observed within 5 Mpc of the cD. It is a more quantitative description of the information graphed in Figs. 2 and 3. Note that the organization of this chart matches the layout of Fig. 2. For each category we include three rows of information: (1) the total number of observations in that category, (2) the total amount of gas mass lost or gained in all the observations, and (3) the total stellar mass change. The total mass changes are in units of $10^{10} M_\odot$. There are a total of 1257 observations.

The galaxies that are observed to lose stars and gain gas (in the lower right quadrant of Fig. 2) are likely to be undergoing two processes within one time step. When we made the same graph using time steps half as long we found only 62.5% of our observations remained in the fourth quadrant. The very small number of galaxies observed to gain stars and lose gas may also be caused by the aggregation of a few processes. Despite this, we chose not to use the smaller time step because in most cases it splits up a single process, resulting in more smaller mass changes along the axes. The points from the central cluster region in the lower right quadrant of Figure 2 are dominated by the largest galaxy that we follow (7 of 10 points). These points may be caused by the galaxy being physically stripped by the cD while it is unphysically overcooling surrounding gas.

The galaxies losing both gas and stars may be undergoing galaxy harassment or tidal stripping by either the cD or a nearby galaxy. In a parallel process, the galaxies that are gaining both gas and stars are either merging or accreting both gas and stars from their surroundings or a nearby galaxy. We found a lower limit of three mergers by counting the number of tracked pairs that merge within a radius of 5 Mpc from the cD. It is interesting that all three of these mergers involve galaxies with gas, and all three merged galaxies continue to contain cool gas throughout the simulation.

The points in Figure 2 are coded by the galaxy’s minimum distance from the central cD during each time step; diamonds are within 1 Mpc, triangles are within 2.4 Mpc, and squares are out to 5 Mpc. It is clear from a visual inspection of the plot that many of the central galaxies are either gasless galaxies undergoing a tidal process or galaxies undergoing gas stripping. The galaxies in the periphery are the majority of the galaxies gaining gas, as
spirals are conjectured to do in the field (Larson et al. 1980). The transition region galaxies are not so easily categorized, and seem to consist of galaxies undergoing processes more clearly associated with one of the other two regions. On a qualitative scale, our graph compares well with T03’s Figure 10 in that we see more ISM-ICM interactions close to the cD and mergers spanning the entire 5 Mpc: three of the points in the first quadrant of Figure 2 are mergers between tracked galaxies, two of which are in the central region and one of which is in the periphery.

In Figure 3 we look more closely at the points that lie along the positive or negative x-axis, and generate the distribution of gas mass loss and gain, again coded by the galaxy distance from the cD. The left histogram shows that most of the RPS occurs in galaxies in the central region, but does also have some impact on galaxies in the transition region and, to a lesser extent, the periphery. Furthermore, the right histogram shows that gas accretion is occurring, and occurs mostly to galaxies in the periphery. There is a significant drop in the number of galaxies accreting gas in the transition region in comparison to the periphery, and we may be seeing the region where starvation begins to occur (Larson et al. 1980).

3.3. Ram Pressure Stripping

Of the 107 observations in which a galaxy loses gas by a mechanism other than star formation, at least 84 fit our criteria for ICM-ISM interactions (refer to Table 2). In order to better examine how $\Delta M_{\text{gas}}$ changes with radius, we plot $\Delta M_{\text{gas}}$ against the distance from the central cD, still removing star formation. Figure 4 shows that there is an increase in both the amount of gas mass lost and the number of galaxies losing gas, with decreasing distance from the cD. This trend is strongest for $r < 1$ Mpc, but begins at about 2 Mpc, significantly beyond the 1 Mpc radius T03 had used as the edge of high ICM density.

To clarify the reason for this trend, we calculated the ram pressure as first derived by Gunn & Gott (1972): $\rho v^2$, where $\rho$ is the ICM density and $v$ is the relative velocity between the ICM and the ISM. Gas was defined to be part of the ICM if it had a temperature above $5 \times 10^6$ K. The density was calculated for all the hot gas in a sphere of radius 90 kpc centered on a galaxy center previously identified by HOP. To find the velocities of the ICM and ISM we averaged the velocities of all the individual cells of gas that were included in the 90 or 26.7 kpc sphere, respectively. We then took the magnitude of the velocity difference to use in our ram pressure calculation. Figure 5 shows how ram pressure varies with distance from the cD: there is a definite increase of ram pressure with decreasing distance to the cluster center beginning at about 2 Mpc. This correlates well with the increasing gas loss with decreasing distance to the cD. It is also important to note that $\rho v^2$ varies by about 2 orders of magnitude at a given radius. This is partially due to the density and velocity structure in the ICM, which is apparent in the simulations, and partially due to the wide range in galaxy velocities at a given radius. To illustrate the importance of this effect, we can see that, for example, at 2 Mpc from the cD, ram pressure is often below the value of $10^{-12}$ derived by Gunn & Gott (1972) to be the minimum ram pressure for effective stripping, but there are some observations of higher ram pressure values.
The cluster. Of the cluster there is an increase in ram pressure, evidence that ram pressure is indeed the cause of the increase in gas loss seen in the galaxies in the inner region of the cluster.

Although most of the points with a large amount of gas loss and high ram pressure are from galaxies within the inner 1 Mpc of the cluster, there are a few galaxies that seem to be ram pressure stripped from the transition region, consistent with our interpretation of Figures 4 and 5.

While the correlation with ram pressure strength is indicative of a role for ram pressure stripping (RPS), we should note that we do not exclude viscous stripping and other mechanisms that scale in a similar way. In the following, we refer to these processes collectively as RPS.

3.4. Case Studies of Gas-stripped Galaxies

To examine the stripping process in more detail, we examined the 16 galaxies that went from having a cool gas mass of more than $3.16 \times 10^9 M_\odot$ at $z \sim 0.35$ to having no cool gas by the end of the simulation. We chose this mass loss cutoff because it is the limit of our constant category, as discussed earlier. Of the 119 observations of these 16 galaxies, 37% fit our gas loss criteria, for a total cool gas mass loss of $3.86 \times 10^{11} M_\odot$, caused by all mechanisms (other than star formation). Of the observations of galaxies losing gas, 89% have no change in stellar mass, which we take to indicate RPS (or a related mechanism). These observations are distributed among 13 of the 16 galaxies, for a total of $3.25 \times 10^{11} M_\odot$ gas mass lost by RPS.

To verify that we are not merely seeing a part of a longer episode of tidal stripping or galaxy harassment that included only gas loss for a subset of the observations, we looked at the four observations in which both gas and stars were lost. Only one of these was of a galaxy that also contained an observation of pure gas stripping. Even ignoring this galaxy, 88% of gas loss observations are of RPS. To be conservative in our number of ram pressure stripped galaxies, we assumed that the galaxy that had only gas loss followed by both gas and stellar mass loss did not undergo RPS. Thus, we only include 12 galaxies in our RPS statistics.

Next, we considered where in the cluster these galaxies were being stripped. Although most of the galaxies undergoing RPS were in the central region of the cluster, 40% of the observations were of galaxies in the transition region. Of those in the transition region, only 13% were of galaxies that had been within 1 Mpc of the center since $z \sim 0.35$. Thus, most of our observations of galaxies undergoing RPS in the transition region were beginning the ISM-ICM interaction there. We even observed a single galaxy being ram pressure stripped in the periphery for $\sim 2.5$ Gyr. This galaxy was also unique in that it had lost all of its gas before reaching the central region of the cluster.

Finally, we can give a rough estimate (because our time resolution is 0.244 Gyr) of the length of time it took galaxies to lose their gas once gas loss began. This is a worthwhile estimate for comparison to T03, who define any ISM-ICM interaction that is longer than 1 Gyr as starvation. We find that five of the 12 galaxies fulfilling our RPS requirement lose their gas in about 1 Gyr. However, we also find that five galaxies lose their gas in well over 1 Gyr, and only two galaxies lose their gas in much less than 1 Gyr. This is in tentative agreement with T03’s conclusion that galaxy transformation is generally a slow process.

In order to illustrate some of the possible evolutionary paths of the galaxies that lose all their gas, we choose four galaxies to discuss in detail. In Figure 7 for each of the galaxies, we plot four quantities as a function of time: (1) the total stellar mass of the galaxy, (2) the total gas mass of the galaxy, (3) the amount of mass that will form stars in the next 0.244 Gyr, and (4) the distance from the cD. In this figure, because we also plot the amount of star formation, we do not attempt to make any corrections to the gas or stellar mass to account for it.

The galaxy in Figure 7a, galaxy A, is most representative of the 16 galaxies we examine in detail, both in terms of mass and evolution. When we begin to track this galaxy, it has more stellar mass than gas mass, although only by about a factor of 3. Galaxy A’s orbit is the most circular of the four chosen galaxies, and we may see most of a circuit of galaxy A around the cD. This galaxy gains gas in the first 0.244 Gyr of our observations. Early gas accretion is common in our sample of stripped galaxies, as 56% of the galaxies that eventually lose all their gas first gain gas for at least one time step. It is also not uncommon for a galaxy to gain cool gas...
mass within the transition region, as this galaxy does. However, immediately after galaxy A accretes cool gas, its gas is stripped for 0.732 Gyr. This is one of the faster stripping events we observe. All the stripping occurs within the central region of the cluster, as predicted by T03. Once the galaxy is stripped of its gas (after about 1 Gyr of observations), there are no more significant changes to its mass.

In Figure 7b, our observations of galaxy B begin when this galaxy has almost the same amount of gas and stellar mass. This indicates that we may be observing the first time this galaxy has entered the central region of the cluster. Most of the increase in stellar mass is due to star formation, and we see that it ends when there is no more gas in the galaxy. All of the small ripples in the stellar mass of the galaxy are too insignificant to be outside of our zero range of $10^{11} M_\odot$. The orbital path is consistent with a first entry into the cluster environment, and like galaxy B, the stellar mass increases slightly while the galaxy has gas because of star formation. As with galaxy A, this galaxy accretes gas before it starts to be stripped. This galaxy, like half of the galaxies that undergo RPS, begins being stripped of gas in the transition region, before it enters the central region of the cluster. Galaxy C is stripped as far from the cD as 1.7 Mpc. After 1.5 Gyr this galaxy has no more gas. Nearly 2.5 Gyr after we begin observing this galaxy it is stripped of a small amount of stars. At this point the galaxy has passed its closest approach to the cD by almost 1 Gyr and 1 Mpc, so it seems unlikely that material is being stripped by the cD. Late stellar mass loss is not uncommon: 56% of the galaxies that become gasless go on to lose stars for at least one time step. We speculate that this is due to galaxy harassment.

**Fig. 7a**

**Fig. 7b**

**Fig. 7c**

**Fig. 7d**

**Fig. 7.**—Plot in each graph of four items against time: (1) *Dot-dashed lines*, the total stellar mass of the galaxy, for (a) in units of $10^{11} M_\odot$, for (b–c) in units of $10^{10} M_\odot$, and for (d) in units of $10^{12} M_\odot$; (2) *solid lines*, the total gas mass of the galaxy (in units of $10^{10} M_\odot$); (3) *dotted lines*, the amount of mass that will form stars in the next 0.244 Gyr (in units of $10^{10} M_\odot$); and (4) *dashed lines*, the distance from the cD (in megaparsecs). In this figure, because we also plot the amount of star formation, we do not attempt to make any corrections to the gas or stellar mass to account for it. See § 3.4 for discussion. [See the electronic edition of the Journal for a color version of this figure.]
The galaxy in Figure 7d, galaxy D, is one of the five most massive galaxies we observe in our simulation. We begin following this galaxy as it falls from the transition region into the central region; however, with our limited amount of orbital information, we cannot tell whether this galaxy is falling toward the central region for the first time. In this galaxy the amount of stellar mass is 2 orders of magnitude larger than the amount of gas mass. The extremely small amount of gas mass leads us to believe that this galaxy has been influenced by the cluster environment for some time. The gas mass lost in the first 0.244 Gyr is almost entirely due to star formation. As galaxy D enters the central region of the cluster, a small amount of both gas and stars is lost. There is another galaxy that we follow that is less than 200 kpc from galaxy D during the second 0.244 Gyr period, and so this may be an example of a galaxy-galaxy tidal stripping event (i.e., harassment). In the third time step, there is no change in the stellar mass of galaxy A, but the rest of the gas mass is lost. Although we measure this as RPS, we hesitate to make a definitive categorization because it follows a time step in which both gas and stars are lost. Once the gas is stripped from galaxy A, there is no significant change in stellar mass until ~1.5 Gyr into our tracking. At this point, $4.31 \times 10^{10} M_{\odot}$ is lost in one time step and $9.86 \times 10^{10} M_{\odot}$ in the next. Again, the galaxy has passed its closest approach to the cD (by almost 0.5 Gyr and 0.5 Mpc). After this ~0.5 Gyr stellar stripping event, the galaxy undergoes no more significant mass changes.

There are a few important points that this subsample of galaxies highlights. First, approximately 75% of the galaxies that lose all their gas are affected by RPS, often losing most of their gas by this mechanism. In half of the ram pressure stripped galaxies, the stripping begins in the transition region, farther than assumed by T03, although most of the gas is lost in the central region. As discussed in § 1, there have been observations of RPS far from the cluster center. Gas stripping tends to be a long process, generally taking at least 1 Gyr. Also, once these galaxies lose their gas, over half of them undergo a stellar stripping event that is not clearly due to the cD.

4. CONCLUSIONS

In this paper we have presented a first examination of how the gas and stellar content of galaxies evolve within a cosmological simulation of a cluster of galaxies. We use a high-resolution simulation that includes the required gas, dark matter, and stellar physics in order to find out how and when galaxies lose their mass. Our main results are the following:

1. We have tracked 132 galaxies through time in a detailed simulated cluster environment. We make comparisons with recent observations, specifically those of T03. Like T03 we split our cluster into three regions: central region ($r < 1$ Mpc), transitional region ($1 < r < 2.4$ Mpc), and the periphery ($r > 2.4$ Mpc). We find a relation between the cluster radius and galaxy gas content that is qualitatively similar to that found by T03 (see Table 1), although we note that a detailed comparison is difficult by our inability to assign a reliable morphological class to our simulated galaxies.

2. Most of the gas lost from galaxies in our simulations is lost in a gas-only event (i.e., the stellar mass is unchanged). These events are preferentially found in the central region, but can occur as far out as 2 Mpc from the cluster center. We find that the amount of gas loss correlates with the ram pressure experienced by the galaxy, indicative of a ram pressure origin to the gas loss. At fixed radius from the cluster, there is a wide variation in the ram pressure strength experienced by a given galaxy.

3. We observe mergers both in the central region of our cluster as well as in the periphery, consistent with T03. We do not observe any dry mergers (although they might occur in the galaxies we do not follow), and none of the mergers we follow exhaust the gas supply of the participating galaxies. Furthermore, we observe disruptions of both the gas and stellar mass in galaxies in all three regions that could be attributed to galaxy harassment or other galaxy-galaxy interactions (Fig. 2 and Table 2).

4. Galaxies in the periphery and field ($r > 2.4$ Mpc) are observed to accrete cold gas; however, this accretion is largely suppressed for galaxies in the transition and central regions ($r < 2.4$ Mpc). We interpret this as starvation caused by the ICM.

5. By examining in detail the galaxies that lose all their gas, focusing on four different cases in particular, we were able to draw more detailed conclusions about this small subset of 16 galaxies. First, ram pressure stripping (RPS), which affected at least 12 of these galaxies, is the dominant mechanism causing galaxies to lose their gas. RPS began in the transition region for half of the stripped galaxies, and in one case in the periphery. In agreement with T03, we find that gas stripping tends to occur on timescales $\geq 1$ Gyr. Although these total gas stripping events may begin as starvation, only affecting the outer halo gas associated with these galaxies, they clearly end by removing any gas that would have been in the galactic disk. As addressed above, we cannot make any claims about the fate of dense molecular gas. We also found that many galaxies, once they lost their gas, also lost a significant amount of stellar mass. It was not clearly correlated with a galaxy’s closest approach to the cD, nor was it followed by a merger. This finding may lend tentative support to galaxy harassment as an important mass stripping mechanism.

We interpret these results to mean that the decrease in gasless galaxy fraction with increasing cluster radius can be explained by environmental mechanisms out to almost 2 Mpc. This result parallels observational findings by, e.g., Solanes et al. (2001). ISM-ICM interactions are important out to this large radius, and RPS may have a large role in transforming spirals into S0s out to this distance. The ICM in our simulation has significant structure, which can been seen in the spread of ram pressure values at any cluster radius in Figure 5. A similar range of ICM density at different clustercentric radii is seen in our simulations, and density variations have also been observed (e.g., Bohringer et al. 1994). The ICM’s structure could explain why it is more important than in the simple assumptions used by T03. However, the stripping process can be very slow ($\geq 1$ Gyr), and therefore conforms to the broad definition of starvation used by T03.

We make clear predictions about RPS, and can compare the mass evolution caused by galaxy-galaxy and galaxy-cluster interactions with that caused by ISM-ICM interactions. However, we do not compare galaxy-galaxy and galaxy-cluster interactions. This is because these interactions can have the same signature effects on the gas and stellar mass of a particular galaxy. In order to make any comparisons we will have to make detailed calculations about the force over time of nearby galaxies and the cD. Also, although we see definite trends with radius, we have not begun to look at whether there is a relation between the local density of galaxies and evolutionary mechanism. These will wait for a future examination.

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outside of a small dense disk. Based on these results we are confident that our resolution is high enough to measure the amount of cool gas a galaxy may lose. We have performed a set of more detailed single-galaxy simulation runs to verify that our results are resolution independent. We use the galaxy model of Roediger & Brüggen (2006), with the addition of radiative cooling (but no star formation). The ICM temperature and density are $4.385 \times 10^7$ K and $10^{-28}$ g cm$^{-3}$, respectively. The two runs we present here have resolutions of 304 pc and 2.43 kpc. As necessitated by the different resolutions, the gas disk scale height in the $z$-direction increases from 0.4 to 4.0 kpc. We perform runs with two velocities, a subsonic and supersonic case: $8.0 \times 10^3$ and $2.53 \times 10^3$ cm s$^{-1}$. Unlike Roediger & Brüggen (2006), all of the ICM in our simulation instantaneously begins to move at the wind speed. As in our paper, we follow the cool ($T \leq 15,000$ K) gas mass within a sphere with a radius of 26.7 kpc. Although we start with no gas cooler than 15,000 K, most of the gas within the galaxy quickly cools to below our upper limit.

We show our results in Figure 8. As seen in the top panel, very little gas is lost in either of the galaxy models in the subsonic run. In the supersonic run shown in the bottom panel, the galaxy with the smaller scale height and higher resolution initially loses cool gas more quickly. However, the disk with higher resolution keeps a smaller disk of cool gas, while the lower resolution disk continues to slowly be stripped of its gas with time. Because we do not include star formation, we are missing the energy that would be input by the resulting supernovae and increase the height of the disk. We perform a simulation without radiative cooling, and therefore with a thicker disk, and find that the gas loss between galaxies of different resolutions is more similar. We expect that including star formation results in disks with larger $z$-scale heights, and therefore that the gas loss measured in the galaxies in the cosmological simulation is less affected by resolution differences than in the galaxies we show here (with only radiative cooling). Similar results are found when the galaxy is edge-on to the wind. As shown in Figure 8, although the gas loss history differs in the two models, the difference is never less affected by resolution differences than in the galaxies we show here (with only radiative cooling).

## APPENDIX

### RESOLUTION STUDY

We show our results in Figure 8. As seen in the top panel, very little gas is lost in either of the galaxy models in the subsonic run. In the supersonic run shown in the bottom panel, the galaxy with the smaller scale height and higher resolution initially loses cool gas more quickly. However, the disk with higher resolution keeps a smaller disk of cool gas, while the lower resolution disk continues to slowly be stripped of its gas with time. Because we do not include star formation, we are missing the energy that would be input by the resulting supernovae and increase the height of the disk. We perform a simulation without radiative cooling, and therefore with a thicker disk, and find that the gas loss between galaxies of different resolutions is more similar. We expect that including star formation results in disks with larger $z$-scale heights, and therefore that the gas loss measured in the galaxies in the cosmological simulation is less affected by resolution differences than in the galaxies we show here (with only radiative cooling). Similar results are found when the galaxy is edge-on to the wind. As shown in Figure 8, although the gas loss history differs in the two models, the difference is never large. Based on these results we are confident that our resolution is high enough to measure the amount of cool gas a galaxy may lose outside of a small dense disk.

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![Figure 8](image-url)  
Fig. 8.—Gas mass evolution of galaxies with different resolutions in a subsonic (top) and supersonic (bottom) wind. The solid line is a galaxy with 304 pc resolution based on the model Roediger & Brüggen (2006), while the dash-dotted line is a galaxy with 2.43 kpc resolution based on the same model but with a $z$-scale height 10 times larger. The difference in gas loss is small enough that we are confident that our resolution is sufficient for following gas loss.
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