On the Origin of Gas-poor Galaxies in Galaxy Clusters Using Cosmological Hydrodynamic Simulations

Seoyoung L. Jung1, Hoseung Choi1, O. Ivy Wong2, Taysun Kimm1, Aeree Chung1, and Sukyoung K. Yi1

1 Department of Astronomy, Yonsei University, 50 Yonsei-ro, Seodaemun-gu, Seoul 03722, Republic of Korea; yi@yonsei.ac.kr
2 International Centre for Radio Astronomy Research (ICRAR), University of Western Australia, 35 Stirling Highway, WA 6009, Australia

Received 2018 June 11; revised 2018 August 27; accepted 2018 August 27; published 2018 October 4

Abstract

The environmental effect is commonly used to explain the excess of gas-poor galaxies in galaxy clusters. Meanwhile, the presence of gas-poor galaxies at cluster outskirts, where galaxies have not spent enough time to feel the cluster environmental effect, hints at the presence of preprocessing. Using cosmological hydrodynamic simulations on 16 clusters, we investigate the mechanisms of gas depletion of galaxies found inside clusters. The gas-depletion mechanisms can be categorized into three channels based on where and when they took place. First, 34% of our galaxies are gas poor before entering clusters (“preprocessing”). Some of them were group satellites that are low in gas at the time of cluster entry compared to the galaxies directly coming from the field. Even the galaxies with large gas fractions take this channel if they fall into massive clusters ($\gtrsim 10^{14.5} M_\odot$) or approach cluster centers through radial orbits. Second, 24% of the sample quickly became gas deficient in clusters before the first pericentric pass (“fast cluster processing”). The relative importance of each channel varies with a cluster’s mass, while the exact degree of significance is subject to large uncertainties. Group preprocessing accounts for one-third of the total gas depletion, but it also determines the gas fraction of galaxies at their cluster entry, which in turn determines whether a galaxy should take the fast or slow cluster processing.

Key words: galaxies: clusters: general – galaxies: evolution – galaxies: groups: general – methods: numerical

1. Introduction

Earlier observations of external galaxies demonstrated that the physical properties of galaxies depend on their surrounding environment. Galaxies in dense, crowded environments predominantly have early-type morphology (e.g., Oemler 1974; Davis & Geller 1976; Dressler 1980; Postman & Geller 1984), red color (e.g., Pimbblet et al. 2002; Hogg et al. 2003; Balogh et al. 2004; Baldry et al. 2006), reduced star formation activity (e.g., Balogh et al. 1997; Poggianti et al. 1999; Lewis et al. 2002; Kauffmann et al. 2004; Wetzel et al. 2012), and low neutral hydrogen (H I) content (e.g., Haynes & Giovanelli 1984; Fabello et al. 2012; Hess & Wilcots 2013). The environmental effect is commonly used to explain these observed trends. By splitting galaxies into centrals and satellites, researchers found that satellite galaxies are more likely to be red, quenched, and gas poor compared to the central galaxies with the same stellar mass and host halo mass ranges (van den Bosch et al. 2008; Weinmann et al. 2009; Wetzel et al. 2012; Catinella et al. 2013). Considering the hypothesis of van den Bosch et al. (2008) that galaxies are first born as centrals of their own dark matter halo and then may become satellites as they fall into a larger halo, the distinction in the quenched galaxy fraction between the central and satellite populations appears to be due to the transformation mechanisms that affect satellites predominantly. Peng et al. (2012) discovered that the dependence of the red galaxy fraction on their local environment vanishes for central galaxies (see also Kimm et al. 2009). Therefore, we can say that the observed excess of red galaxies in dense environments is governed by satellite-specific mechanisms.

Galaxy clusters are among the most massive systems in the universe. In this extreme environment, the host dark matter halo and its brightest cluster galaxy dominate their satellites in terms of mass, so the effects of satellite-specific processes are more prominent in clusters than in less massive systems. In this sense, clusters are the best test beds for studying the environmental effect.

When focusing on one massive cluster halo, the number of early-type, red, and gas-deficient galaxies is highest at the center of the halo and gradually becomes smaller toward the outskirts (Whitmore et al. 1993; Balogh et al. 1999; Solanes et al. 2001; Gómez et al. 2003; Gavazzi et al. 2006; von der Linden et al. 2010; Bahé et al. 2013). By assuming that a radial distance from the cluster center to a galaxy roughly indicates the time since infall to the cluster (e.g., Rhee et al. 2017), the transformation of galactic properties according to their distance from the cluster center can be interpreted as the time evolution of galaxies falling into the cluster. When a galaxy moves from a field environment to a dense environment, it experiences physical processes that are active in dense environments, causing the galaxy to lose its gas. In particular, low-density gas, which is mainly observable in the form of H I emission, is highly fragile to the environmental effect as it is diffuse and typically extended beyond the stellar disk (e.g., Fouque 1983; Giovanelli & Haynes 1983; Hewit et al. 1983). The absence of galactic gas leads to the cessation of star formation. If there is no additional supply of cold gas from outside to refuel the star formation, a galaxy soon becomes red.

Indeed, many mechanisms have been proposed to explain how the environment induces the transformation of galactic properties. Due to the high galaxy number density in massive clusters compared to typical regions of the universe, there is a high probability of gravitational interactions with neighbor galaxies...
inside clusters. Harassment (Moore et al. 1996) is a fast encounter between galaxies and is common. Mergers induce violent morphology transformation (Toomre & Toomre 1972) but are assumed to be rare in massive clusters due to high relative speeds. At the same time, a galaxy can interact with the dark matter halo potential, undergoing a tidal stripping of both gas and stars (Byrd & Valtonen 1990; Bekki 1999). X-ray observations covering dense cluster regions have revealed that massive dark-matter halos are filled with hot intracluster medium (ICM; Sarazin 1986; Neumann & Arnaud 1999; Pratt & Arnaud 2002). As a galaxy moves through the ICM, it experiences the ram pressure that strips off the interstellar medium (ISM) and becomes a gas-poor galaxy (Gunn & Gott 1972; Quilis et al. 2000). When the ram pressure is weak and merely able to strip hot surrounding halo gas, the galaxy slowly runs out of the cold gas without additional gas supply from hot gas cooling; that is, starvation ( Larson et al. 1980). Moreover, thermal evaporation due to the hot ICM can lead to the loss of galactic ISM (Cowie & Songaila 1977).

Numerous studies have attempted to estimate the gas-depletion timescale or star-formation quenching timescale to obtain an insight into the physical processes responsible for the environmental effect. Using the Blind Ultra Deep H I Environmental Survey (BUDHIES), Jaffé et al. (2015) discovered that H I depletion of BUDHIES galaxies takes place before the first pericentric pass. They found a higher fraction of H I detected galaxies among the first infalling galaxies (67%) than among the virialized ones (14%) and claim that ram pressure stripping is the key mechanism for gas depletion. Regarding the star-formation quenching timescale, Mahajan et al. (2011) used phase-space analysis and found that their observed galaxies seem quenched during the first passage through the cluster. Meanwhile, Wetzel et al. (2013) advocated a “delay then rapid” quenching model that matches the observed bimodality of the specific star formation rate among Sloan Digital Sky Survey (SDSS) cluster satellites. According to their model, galaxies keep forming stars after they pass their first pericenter. Indeed there is a significant amount of mass increase through star formation activity among their galaxies, between cluster infall and redshift zero. See also Tollet et al. (2017), who found that the quenching model, in which the star formation activity of infalling galaxies is sustained at least during the first infall, matches the observed stellar mass function in groups and clusters.

“Preprocessing” seems to be another channel that produces an excess of gas-poor, quenched populations in clusters (Fujita 2004). For example, Wetzel et al. (2013) claimed that the observed difference in the passive galaxy fraction as a function of the host halo mass is only due to the variation in the contribution of the preprocessed galaxies in each halo. Observations on cluster vicinities reported that some galaxies outside the virial radius of the cluster are already red, gas deficient, and quenched even though they are unlikely to have experienced the environmental effects of the cluster yet (Jaffé et al. 2015; Jaffé et al. 2016). In particular, group-size halos are probable sites of preprocessing (Cortese et al. 2006; Just et al. 2015; Bianconi et al. 2018). Through the hierarchical assembly, group-size dark matter halos dive into massive clusters, guiding their associated galaxies, some of which are already in a gas-deficient state, to be members of the clusters. There is growing evidence of a moderate environmental effect in groups, resulting in a higher fraction of early-type, passive, gas-poor galaxies compared to the field environment (Postman & Geller 1984; Zabludoff & Mulchaey 1998; Cybulski et al. 2014; Barsanti et al. 2018). Therefore, it is important to estimate the significance of preprocessing in producing the passive, gas-poor galaxies observed in clusters.

In this study, we use a set of cosmological hydrodynamic simulations (Choi & Yi 2017) to explore both preprocessing and the environmental effect inside clusters. The novelty of this simulation is that we have 16 clusters with a variety of halo masses reaching up to $M_{200} \approx 10^{15} M_\odot$ by using the “zoom-in technique” from a large cosmological volume (see Section 2.1 for details). Our goal is to trace back the gas history of galaxies and investigate possible channels that produce gas-poor galaxies found in clusters. More specifically, we try to answer the following questions: (1) when and where did the gas-depletion processes take place?, and (2) what is the timescale of gas depletion inside clusters?

This paper is structured as follows. In Section 2, we describe our simulations, present the method for measuring the gas properties of galaxies, and define the term gas-poor galaxy, which is the central concept of this paper. In Section 3, we demonstrate what can be inferred from the radial distribution of gas-poor galaxies. Section 4 provides an in-depth discussion of preprocessed galaxies, galaxies that become gas poor before entering the clusters. This section includes a discussion on how many galaxies are preprocessed and under what conditions is the preprocessing efficient. In Section 5 we examine galaxies that are depleted of their gas inside the cluster halo. We mainly focus on the timescales of being gas-poor galaxies in clusters and investigate what determines the depletion timescale. In Section 6.1, we briefly discuss the signs of active ram pressure stripping both in groups and clusters. Finally, in Section 7, we present three possible scenarios for producing gas-poor galaxies and compare their relative importance.

## 2. Methods

### 2.1. Numerical Simulation

We used the Yonsei Zoom-in Cluster Simulation (YZiCS; Choi & Yi 2017), which was performed using the adaptive mesh refinement (AMR) code RAMSES (Teyssier 2002). We adopted a cosmology based on the seven-year Wilkinson Microwave Anisotropy Probe (WMAP) data (Komatsu et al. 2011): a Hubble constant of $H_0 = 70.4 \pm 1.3$ km $s^{-1}$ Mpc$^{-1}$, a baryon density of $\Omega_b = 0.0456$, a total matter density of $\Omega_m = 0.272$, a dark energy density of $\Omega_{\Lambda} = 0.728$, an rms fluctuation amplitude at $8 h^{-1}$ Mpc of $\sigma_8 = 0.809$, and a spectral index $n = 0.963$. We first ran a dark-matter-only simulation for a $200 h^{-1}$ Mpc cube, from which 16 clusters were selected and resimulated with the maximum physical resolution of $0.76 h^{-1}$ kpc. Thanks to the large parent volume, our sample contains galaxy clusters of mass $5 \times 10^{13} < M_{200}/M_\odot < 10^{15}$. The zoom-in simulations cover the volume out to the clustocentric distance to the farthest particle in the initial stage ($z = 50$) among all the dark matter particles inside $3R_{200}$ of the cluster at $z = 0$. Figure 1 shows the projected distributions of gas density and AMR grids within $3R_{200}$ of one of the YZiCS clusters with mass log $M/M_\odot \sim 14.74$ at redshift zero. It demonstrates that our AMR approach traces the gas structure: all density peaks within $3 R_{200}$ of the cluster are at least at $1.5 h^{-1}$ kpc, while low-density regions are resolved at a few $h^{-1}$ kpc. The simulation results were saved at a constant interval of a scale factor, $\Delta a_{\text{exp}} \approx 0.005$, except for very early epochs, resulting in a total of 187 snapshots.

We adopt the baryon prescriptions of Dubois et al. (2012). A brief summary is as follows. Gas cooling by primordial species...
(H and He) is modeled assuming collisional ionization equilibrium, while metallicity-dependent cooling is included using Sutherland & Dopita (1993). Heating due to the ultraviolet background radiation (Haardt & Madau 1996) is turned on at $z = 10$. Star formation takes place in cells with hydrogen number densities above $n_h = 0.1 \text{ cm}^{-3}$ (Rasera & Teyssier 2006; Dubois & Teyssier 2008) following the Schmidt law $\dot{\rho} = \varepsilon_s \rho_g / t_{ff}$, where $\rho_g$ is the gas density, $t_{ff} = (3\pi / (32G))^{1/2}$ is the local free-fall time, and $\varepsilon_s$, the star formation efficiency per free-fall time, is set to 2% (Kennicutt 1998). Feedback from supernovae Type II is modeled assuming a Salpeter (1955) initial mass function. Seed black holes with a mass of $10^5 M_\odot$ form in dense cells where $\rho_0 > 0.1 \text{ cm}^{-3}$ and Jeans’s criterion is violated. Accretion onto black holes is modeled by the Bondi–Hoyle–Lyttleton accretion (Hoyle & Lyttleton 1939; Bondi & Hoyle 1944). When the gas accretion rate is low, black holes launch bipolar jets (radio mode), whereas the active galactic nuclei deposit thermal energy isotropically when the accretion rate is high (quasar mode; Dubois et al. 2012).

2.2. Galaxy Identification

The galaxies in the simulation were identified using Halo-Maker through the AdaptaHOP method (Aubert et al. 2004), with the most massive subnode mode (Tweed et al. 2009) applied for star particles. The mass resolution of star particles is $5 \times 10^5 M_\odot$. A minimum of 2000 particles, that is, a stellar mass of $10^9 M_\odot$ at $z = 0$, are required to be identified as a galaxy. Using a galaxy merger tree, we follow their most massive progenitors up to redshift two. To avoid galaxies with poorly constructed merger trees, we restrict our sample to galaxies linked in more than 100 snapshots among the 187 snapshots we have. The resulting number of galaxies at $z = 0$ is 3818.

2.3. Gas Properties of Simulated Galaxies

Due to the Eulerian nature of the AMR technique, gas cells are nontraceable entities throughout the entire volume but are redefined in every snapshot instead. Nevertheless, since we are interested in the integrated gas properties of individual galaxies and their surroundings, for example, the total cold gas mass of a galaxy and surrounding ICM density, the changes over time were tracked by linking the gas properties of galaxies measured at each snapshot with a galaxy merger tree.

The gas cells tend to settle at thermodynamically quasi-stable phases, with an excess of a population at the corresponding density and temperature. In Figure 2 the gray-scale shades show the mass-weighted 2D histogram of all of the simulated gas cells within $3R_{200}$ of a cluster at redshift zero. There is an excess of cells at $T \sim 10^{7.8} \text{ K}$ and $\sim 10^4 \text{ K}$, which correspond to the hot halo gas and galactic gas, respectively. The former phase forms when gas falls into massive dark matter halos ($M_{200} > 10^{12} M_\odot$) and is shock heated to the virial temperature; for example, $T_{200} \sim 10^{7.8} \text{ K}$ for cluster-size halos with $M_{200} \sim 10^{14} M_\odot$. This gas is in a quasi-hydrostatic state with a cooling timescale longer than the free-fall timescale, and at the same time, feedback from active galactic nuclei also keeps the gas hot. Because our simulations are zoomed-in, dense regions centered on massive halos, most of the gas cells are in the shock-heated hot phase. At the central region where gas density is sufficiently high, the hot gas cools down and forms the galactic cold phase gas (e.g., Rees & Ostriker 1977; White & Rees 1978). At the same time, there is a cold-mode accretion following filaments directly from the outside of the halo that also supplies cold gas to a galaxy, but this channel predominantly takes place in less massive halos at high redshift (e.g., Kereš et al. 2005; Dekel & Birnboim 2006).

Note that our simulation does not resolve extremely cold and dense gas phases that exist in real galaxies, like cold molecular gas. Instead we adopt a polytropic equation of state for the gas cells with their density higher than $0.1 \text{ cm}^{-3}$ with the choice of $\gamma = 4/3$ to prohibit gas cells from artificial fragmentation induced by the resolution limit (Schaye & Dalla Vecchia 2008). In this case, the minimum gas temperature is determined by the equation of state, and we can find these star-forming gas cells lie on a straight line with a slope of $1/3$ on the logarithmic $\rho-T$ plane (note the short tail on the right side of the blue dashed contour of the galactic gas).

Figure 1. Gas density (left) and AMR grid (right) map of gas cells within $3R_{200}$ of a cluster with log $M_{200}/M_\odot = 14.74$ at redshift zero. Each color-edge square in the grid map represents a gas cell with a spatial resolution that corresponds to the numbers on a box with the same color on the right. The circles at the center represent $R_{200}$ of the cluster.
from the cells in the yellow shaded area, respectively. Cells within 3 proceed with a linear cooling plane. From the shock-heated hot phase in the top left to the cold gas content of a galaxy.

separate the galactic gas and the ambient medium in order to Figure 2. Distribution of simulated gas cells in the density–temperature plane, weighted with their mass. The gray shades are the distribution of all the gas cells within 3 radii of the cluster, and the yellow shaded area is a 1σ distribution of gas cells within and near one specific galaxy for example. The black dashed line is from Equation (1) of Torrey et al. (2012). The red and blue dashed contours are 1σ distributions of the ambient medium and galactic gas extracted from the cells in the yellow shaded area, respectively.

The yellow shaded area in Figure 2 shows the 1σ distribution of gas cells within and near one specific galaxy in the ρ–T plane. From the shock-heated hot phase in the top left to the cold phase in the bottom right, the gas cells lie in a sequence following a cooling flow. In the following section, we carefully separate the galactic gas and the ambient medium in order to measure the quantities used throughout this paper, for example, the cold gas content of a galaxy.

2.3.1. Ambient Medium and Galactic Gas

The setting of an appropriate size of the region of interest around a galaxy is an important issue. Typical gas-rich galaxies have their cold gas extended beyond their stellar disk (e.g., Fouque 1983; Giovanelli & Haynes 1983; Hewitt et al. 1983). Therefore, in order to contain all the cold gas cells belonging to a galaxy, the boundary of the region should be larger than its stellar distribution, but at the same time small enough to avoid contamination of external gas blobs, such as neighboring galaxies. First, we set $R_{90}$ of the star particles (distance to the top 90% distant star particle from the galaxy center) as a minimum radius to be probed. Then we increase the radius from $R_{90}$ to 6 $R_{90}$ by 1 $R_{90}$ and measure the cold gas mass within each spherical shell. If the cold gas cells reside well within the galactic potential, we expect the cold gas mass within each shell to decrease going outward, but if there is a contribution of external gas blobs, the shell mass would increase sharply at a certain point. Quantitatively, the boundary radius is determined when the shell masses match $dm_i < \epsilon dm_{i+1}$, where $dm_i$ represents the shell mass at the ith shell. A simple isothermal gas sphere would suggest constant shell mass, or $dm_i/dm_{i+1} = 1$. We adopt $\epsilon = 1.2$ to take into account possible small variations caused by the internal structure of a galaxy. The overall results discussed throughout this paper are not significantly affected by the choice of $\epsilon$. For instance, the fraction of gas-poor galaxies changes by less than 0.2% at all snapshots when $\epsilon$ changes from 1.0 to 1.5. If there are no external gas blobs detected within 6 $R_{90}$ of the galaxy, the boundary of the region of interest is set to 6 $R_{90}$, which is typically greater than 100 kpc at redshift zero and roughly comparable with the virial radius of the galaxy. We describe below how the galactic gas and ambient medium were separated from the chunk of gas within this region.

Galactic Cold Gas Cells: We first implement a linear cut in the logarithmic ρ–T plane using Equation (1) from Torrey et al. (2012; see the black dashed line in Figure 2): 

$$\log(T/[K]) = 6 + 0.25 \log(\rho/10^{10} [M_\odot h^2 \text{kpc}^{-3}]),$$

taking the low-temperature side. In real galaxies, the ISM can have multiple phases, from the hot, ionized medium ($\rho \sim 10^{-4} - 10^{-5}$ cm$^{-3}$, $T \sim 10^6 - 10^7$ K) to extremely cold and dense molecular clouds ($\rho \sim 10^{-20}$ cm$^{-3}$, $T \sim 10 - 20$ K). In this study, we define “galactic cold gas” as gas cells roughly in hydrostatic equilibrium, cooled and settled down at $T \sim 10^4 - 10^5$ K. The blue dashed contour in Figure 2 shows the distribution of cold gas cells of an example galaxy. Within our simulation box, the cold gas cells have a density range of $\rho > 10^{-3}$ cm$^{-3}$. With the low-temperature gas cells separated by the linear cut, we perform 3σ clipping on the temperature with the gas cells of densities lower than 0.1 cm$^{-3}$. The gas cells with densities greater than 0.1 cm$^{-3}$, that is, the star-forming cells in our simulation, are always regarded as cold gas.

Ambient hot gas cells: To determine the ambient gas cells, for example, ICM cells, we first impose the same linear cut from Torrey et al. (2012) but take the high-temperature side. In general, the ambient gas cells have low metallicities compared to the metal-enriched galactic gas cells. Therefore, we perform a 3σ clipping on the metallicity to include the relatively metal-poor cells. The red dashed contour in Figure 2 shows the 1σ distribution of the selected gas cells around the sample galaxy on the ρ–T plane. Note that these cells have a $T \sim 10^7$ K that corresponds to the shock-heated hot phase, as discussed above.

2.3.2. Definition of Gas-poor Galaxy

Large H I surveys of the galaxies in the local universe have reported an anticorrelation between the gas fraction ($f_{\text{gas}} \equiv M_{\text{gas}}/M_*$) and stellar mass (Catinella et al. 2010; Huang et al. 2012; Papastergis et al. 2012). The scaling relation extends to the galaxies in cluster environments but with an offset toward the lower gas fraction (Cortese et al. 2011).

In order to compare the gas fraction of YZiCS galaxies with the references, we select the galaxies in low-density regions: the top 20% in terms of the distance to the fifth nearest neighbor at redshift zero. These galaxies are the ones not affected by dense environments, and we confirm that they reveal a similar sequence on the log $M_*$ – log $f_{\text{gas}}$ plane (blue shades in Figure 3).

In this study, we classify a galaxy as “gas poor” when it sufficiently deviates from this gas-rich galaxy sequence toward the lower side. The red dashed line in Figure 3 represents a 2σ clipping result from the black solid line, the linear fit of the gas-rich sequence, along the y axis in log scale. Galaxies under this line (the red shaded region) contain roughly 10% or lower in gas fraction compared to the normal gas-rich galaxies with the same mass, and we call them “gas poor.” Note that we use a log
Therefore, by investigating the first-infall population, we can explore the significance of the environmental effect of the cluster as well as preprocessing effects. On the contrary, PFPP galaxies are the ones that have already gone through multiple pericentric passages and sunk down to the central region of the cluster.

Within 1.5 $R_{200}$ of the clusters, there is a radial trend in the fraction of gas-poor galaxies among the first infalling galaxy sample (the blue line in Figure 4(a)). This strongly suggests that galaxies gradually become gas deficient in their first approach to the cluster center, providing clear evidence for the cluster environmental effect. This topic will be discussed further in Section 5.

Meanwhile, at a distance between 1.5 and 3 $R_{200}$, the fraction of gas-poor galaxies among the first infalling sample remains nearly constant at $\sim 40\%$. It is important to note that the effect of group preprocessing is visible among the galaxies in this distance range. The purple line shows the fraction of gas-poor galaxies among the galaxies that have never been a satellite of any halo over their lifetime (these galaxies are a subsample of the first infalling population). In other words, they have always been a “central” galaxy. This fraction is four times lower ($\sim 10\%$) than the fraction of gas-poor galaxies measured with the entire first infalling sample at similar distance ranges ($\sim 40\%$). In other words, galaxies that pass through the group environment are more likely to become depleted in their gas compared to those who have always been a central galaxy. This topic will be discussed in detail in Section 4.

We now focus on the origin of the radial trend of the whole sample (gray line) in the outer region (1.5 through 3 $R_{200}$). To begin with, the radial trend of the fraction of gas-poor galaxies among the first infalling galaxies (blue shade) is notably weakened at a distance larger than 1.5 $R_{200}$. This implies that the cluster environmental effect is not strong until a galaxy falls inside a cluster (see also Wetzel et al. 2012). On the other hand, PFPP galaxies are almost completely gas poor regardless of their distance from the cluster center (see orange line). Note that the orange histogram in panel (b) shows the radial distribution of PFPP galaxies. The majority of the PFPP galaxies ($\sim 91\%$) reside within 1.5 $R_{200}$ of the cluster. In contrast, some PFPP galaxies with elongated orbits easily reach beyond the virial radius. Quantitatively, $\sim 40\%$ of the galaxies between 1.5 and 2 $R_{200}$ are PFPP, and their contribution decreases to $\sim 14\%$ between 2 and 2.5 $R_{200}$. PFPP galaxies hardly reach distances larger than 2.5 $R_{200}$ (Mamon et al. 2004). As a consequence, even though there is no radial trend among the first infalling galaxies beyond 1.5 $R_{200}$, the decreased population of PFPP galaxies with increasing radial distance from the center results in decline in the gas-poor galaxy fraction of the whole sample (gray line).

In summary, a hint of preprocessing seems clear, and cluster processing is predominantly at work inside $\sim R_{200}$. The overall radial trend of gas-poor galaxy fraction is a result of the combination of preprocessing and cluster processing effects. Based on the discussions made in this section, we explore each process in detail in the following Sections 4 and 5.

### 4. Gas Depletion outside the Cluster Halo: Preprocessing

In this section, we investigate the significance of preprocessing effects in detail. We define “preprocessed galaxy” as a galaxy that becomes “gas poor” (see Section 2.3.2) in at least one snapshot prior to the cluster entry. Therefore, the preprocessing

---

**Figure 3.** Cold gas fraction of YZICS galaxies measured following the method described in Section 2.3.1. The gray dots are the galaxies at redshift zero. The solid black line and blue shaded areas are the linear fit and distribution of the top 20% low-density region galaxies in terms of distance to the fifth-closest galaxy ($D_5$). Colored lines are the gas fraction from H I observations (Catinella et al. 2010; Cortese et al. 2011; Huang et al. 2012). A galaxy is called “gas poor” when it deviates from this gas-rich galaxy sequence more than $\sim 10\%$ (red dashed line, the 2σ clipping).

---

**Figure 4.** The radial distribution of gas-poor galaxies in the sample. The top panel shows the fraction of gas-poor galaxies as a function of distance from the cluster center (1σ clipping result because the gas fraction of galaxies follow lognormal distributions rather than Gaussian (Cortese et al. 2011).
halo. For clusters with a mass range of $10^{14.76} h^{-1} M_{\odot}$, the majority of the infalling galaxies ($\sim 70\%$) arrive at clusters directly from the field, without any neighbor galaxy within their halo. For clusters with a mass range of $10^{14.42-14.76} h^{-1} M_{\odot}$, they argued that preprocessing is uncommon. On the contrary, using the GAlFORM semi-analytic model of galaxy formation, McGee et al. (2009) found that a significant fraction of galaxies enter clusters as group-associated galaxies. Their sample covered massive clusters up to $10^{15.3} h^{-1} M_{\odot}$, and they discovered that galaxies are more likely to be preprocessed in more massive clusters.

Note that both studies define the preprocessed population as galaxies associated with massive halos at the time they arrive at the clusters ($M_{h,\text{infall}} > 10^{13} h^{-1} M_{\odot}$). It is true that galaxies in more massive clusters have a higher chance of being in a gas-deficient state, but this hypothesis may misestimate the fraction of preprocessed galaxies in the following circumstances. In the real universe, not all galaxies within massive halos are gas deficient, and at the same time, some gas-poor galaxies are not associated with a group at the moment of the cluster infall. The former occurs when a satellite does not spend sufficient time to experience the group environment. The latter occurs when a satellite escapes its group halo (or appears to have escaped due to its elongated orbit) after spending sufficient time to suffer the gas depletion. Therefore, instead of using the host mass at the time of the cluster infall ($M_{h,\text{infall}}$), another parameter should be introduced that better reflects the history of the environmental effect.

In Figure 5, we compare two parameters that estimate the host halo mass at the time of infalling galaxies: $M_{h,\text{infall}}$ introduced above and the arithmetic mean value of the host halo masses since $z \sim 2$ until the galaxy reaches the cluster ($M_{h,\text{before}}$). The red and gray points show the preprocessed galaxies and those entering clusters with gas, respectively. The histograms in the top and right panels show the distribution of $M_{h,\text{infall}}$ and $M_{h,\text{before}}$ of each population. The blue area is where $M_{h,\text{before}}$ underestimates the cumulative environmental effect on galaxies before the cluster infall ($M_{h,\text{infall}} < M_{h,\text{before}}$), and the green area is the opposite ($M_{h,\text{infall}} > M_{h,\text{before}}$). The numbers in the boxes on each quadrant are the fractions of the preprocessed galaxy within each quadrant. The preprocessed galaxy fraction correlates better with $M_{h,\text{before}}$ than with $M_{h,\text{infall}}$.
shading) and where \( M_{\text{h,fall}} \) severely overestimates \( M_{\text{h,before}} \) (lower right, green). For visual convenience, we introduced a reference line of \( 10^{12} \ M_\odot \) in this figure.

The numbers in the box in each quadrant show the fraction of preprocessed galaxies. In the top left section (blue), the preprocessed fraction is as high as 50% even though their \( M_{\text{h,fall}} \) is low. This highlights the shortcoming of the use of \( M_{\text{h,fall}} \) as a criterion for preprocessing, as was the case in some previous studies. On the other hand, only 10% of the galaxies are "preprocessed" in the bottom right section (green). Though they are in a relatively massive group at the cluster fall moment, only a small fraction of galaxies appear to be preprocessed, mostly because they have not spent enough time in the current group halo yet. The histograms in the two panels on the top and right sum it up: \( M_{\text{h,before}} \) separates preprocessed and non-preprocessed galaxies better, and thus we have decided to use it in our analysis.

We will now investigate the conditions for which preprocessing becomes most efficient. To see whether the preprocessing mechanism found in our simulation is due to the environmental effect, we first separate our YZiCS sample galaxies into two groups: the central and satellite infallers. At each snapshot, we determine the central and satellite galaxies by comparing their stellar mass at that moment, so that the central galaxies are always more massive than the companion satellites within their host dark matter halo. Note that the locations of galaxies within group halos are not considered when classifying the central and satellites. The sample is then separated into "central infallers" and "satellite infallers." "Central infallers" are the galaxies that have always been the central galaxy of their groups before themselves becoming satellites of clusters. The "satellite infallers" are the remaining, the galaxies that have belonged to groups as satellite galaxies before the cluster infall.

Figure 6 shows the preprocessed galaxy fraction (red color and white numbers on each bin) depending on the \( M_{\text{h,before}} \) and \( M_{\text{h,fall}} \), where \( M_{\text{h,fall}} \) is the stellar mass at the time of the infall. The sample galaxies are separated into (a) central infallers and (b) satellite infallers. The numbers on the top left of each panel show the number of preprocessed galaxies divided by the total number of galaxies that entered clusters. The satellite infallers have an approximately seven times larger preprocessed fraction than central infallers do. Among the 823 satellite infallers, only 30 (3.6%) became gas poor as central galaxies and then later joined a larger group, before the cluster entry. The rest of them deplete their gas as group satellites.

Preprocessing seems significant considering that 45% of satellite infallers become gas poor even before cluster entry. It is more significant on satellites (45%) than in centrals (6%) and on a smaller satellite in a more massive group. This seems natural because galaxies in more massive halos undergo stronger ram pressure as they normally go through a denser intragroup medium with a higher orbital velocity. At the same time, considering that gas stripping through ram pressure is achieved through a competition between ram pressure and gravitational restoring force, lower mass galaxies lose their gas more efficiently under the equal intensity of ram pressure. The importance of and caveats on this issue will be discussed more in Section 6.

This result of more massive galaxies having a higher chance of containing cold gas is seemingly in conflict with the concept of “mass quenching” (e.g., Kauffmann et al. 2003; Baldry et al. 2004). However, in the following discussion, we confirm that this is not the case. Figure 7 shows the fraction of gas-poor galaxies vs. their stellar mass for galaxies that have not yet fallen into clusters until redshift zero. The green and blue lines represent galaxies that have been satellites of larger groups and galaxies that have always been central galaxies, respectively. By separating these two populations, we find opposite trends. As discussed above, satellite galaxies more efficiently become
gas deficient when their stellar mass is small. Conversely, central galaxies show increased gas-poor galaxy fractions with increasing stellar mass, which agrees with the expectation from mass quenching. That is, we verify that there is an indication of the mass effect among our YZiCS galaxies, but the environmental effect is more efficient when their stellar mass is small. Conversely, central galaxies show increased gas-poor galaxy fractions with increasing stellar mass, which agrees with the expectation from mass quenching. On the contrary, for galaxies that have been satellites (green), the environmental effect is extremely efficient, so lower mass galaxies are more likely to be gas poor.

Figure 7. Fraction of gas-poor galaxies as a function of stellar mass. Only the galaxies that have not yet fallen into clusters until redshift zero are presented. Of the galaxies that have always been central galaxies (blue), more massive galaxies are more likely to be gas poor. This trend agrees with the concept of “mass quenching.” On the contrary, for galaxies that have been satellites (green), the environmental effect is extremely efficient, so lower mass galaxies are more likely to be gas poor.

4.2. Preprocessed Fraction Depending on Cluster Mass

Now we examine the preprocessed fraction of each cluster separately to see whether there are any indications of a correlation between the preprocessed fraction and cluster properties. As shown in the previous section, the amount of preprocessed galaxies is linked with how many galaxies underwent the environmental effect in the massive group-size halos before the cluster infall. For clusters that accreted a larger number of massive groups and their constituent galaxies, a higher preprocessed galaxy fraction is expected (see panel (a) of Figure 8). For each cluster, we measure the arithmetic average of $M_{h,\text{before}}$ of cluster member galaxies ($\langle M_{h,\text{before}} \rangle$) to estimate the representative degree of the environmental effect before falling into the clusters. The fraction of preprocessed galaxies linearly increases with increasing $\langle M_{h,\text{before}} \rangle$ (see red dashed line, which is the linear fit).

Meanwhile, using Figure 9, we discover that more massive clusters have a higher chance of accreting massive group halos than less massive clusters (McGee et al. 2009). By separating our clusters into three different mass ranges, we compare the $M_{h,\text{before}}$ values of their member galaxies. Each solid line represents a cumulative fraction of galaxies with higher $M_{h,\text{before}}$ than a given value. For instance, the fraction of galaxies with $M_{h,\text{before}}$ larger than $10^{12} M_\odot$ increases from $\sim$32% to $\sim$45% and $\sim$51% as the cluster mass range increases (see the gray dashed guiding lines). As a consequence, the preprocessed fraction also increases with increasing cluster mass (Figure 8, panel (b)) and the number of cluster member galaxies as well (Figure 8, panel (c)). However, comparing $R^2$ higher than in (a), this is the Pearson coefficient of determination of the linear fit, we find larger scatter in panel (b) and (c) than in (a).

Figure 8. Comparison of the fraction of preprocessed galaxies of the YZiCS cluster sample with different (a) average of $M_{h,\text{before}}$ values of infalling galaxies, (b) cluster halo mass, and (c) number of cluster member galaxies. Error bars are the standard error of the mean of a binomial distribution. The red dashed line in each panel shows the linear fit. $R^2$ presented on the bottom right of the panel is the Pearson coefficient of determination of the fitting.

\footnote{The cluster member galaxies are defined as galaxies that are more massive than $>10^9 M_\odot$ and reside within 1.5 $R_{200}$ of the cluster.}
halos, the environmental effect on their satellites is strong enough to make a good fraction of satellite galaxies gas deficient, even before reaching main clusters. As a result, the contribution of preprocessing to building a gas-poor galaxy population in clusters becomes larger in more massive clusters. Yet, the scatter in the preprocessed fraction among clusters of similar mass and member counts implies that individual galaxy accretion histories of clusters are a fundamental factor in determining the preprocessed galaxy fraction.

4.3. Summary of Preprocessing

In summary, we have demonstrated that $M_{h,before}$ (the average of host halo masses before the cluster infall) is a better indicator than $M_{h,infall}$ (the host halo mass at the time of the cluster entry) in estimating the degree of preprocessing. Preprocessing is found to be more effective on a smaller satellite galaxy in a more massive group, which appears to be consistent with what is expected from the ram pressure stripping process. Finally, preprocessing is more significant in more massive clusters primarily because massive clusters are assembled through more massive groups in the hierarchical paradigm.

5. Gas Depletion inside a Cluster Halo

In the previous section, we discovered that a nonnegligible fraction of galaxies (~30%) arrive at the cluster as gas-poor galaxies. This means that the majority of galaxies are still gas rich at the cluster entry. In this section, we focus on the processes affecting the gas of these galaxies after arriving at clusters. In particular, our main interest is the effect of ram pressure, which is considered as a leading mechanism that induces a severe environmental effect on satellite galaxies falling into massive halos (e.g., Koopmann & Kenney 2004; Tonnesen et al. 2007; Tecce et al. 2010; Kimm et al. 2011; Vollmer et al. 2012).

5.1. How Violent Is the Depletion inside Clusters?

As discussed in Section 3, there is a strong environmental effect acting on our YZiCS galaxies. Figure 10 shows one example of a gas-rich galaxy falling into a cluster. The small figures in panel (a) are gas density maps at given snapshots during the first infall (labeled A, B, C, D, and E). We can see this galaxy loses a significant amount of gas during its first infall, starting from the outskirts, and none of its cold gas is detected at snapshot E. By measuring the cold gas mass at each moment (see columns (2) and (3) of Table 1), we find that the galaxy loses 99.5% of its initial cold gas during its first approach to the center.

We measure the ram pressure intensity that each galaxy goes through following the Gunn & Gott (1972) description:

$$P_{\text{ram}} = \rho_{\text{ICM}} v_{\text{rel}}^2,$$

where $\rho_{\text{ICM}}$ is the mass-weighted average gas density of the ambient medium cells defined in Section 2.3.1, and $v_{\text{rel}}$ is the velocity of a galactic center with respect to the mean motion of the ambient medium. With our definition of the ambient medium, we do not take account of the possible ram pressure that could be caused by other galaxies as the galaxy passed through the neighboring gas.

When galaxies are at their first pericenter, the ram pressure acting on the galaxies is at its maximum strength. The red dashed lines in panels (b) to (e) follow the time evolution of gas content, ram pressure, ambient hot gas density, and velocity of a galaxy with respect to its surrounding hot gas.

The gas content parameter of a galaxy, $\Delta_{\text{gas}}$, is defined as

$$\Delta_{\text{gas}} = \log f_{\text{gas}} - \langle \log f_{\text{gas}} \rangle,$$

where $f_{\text{gas}} = M_{\text{gas}}/M_*$ and $\langle \log f_{\text{gas}} \rangle$ is the mean gas fraction of the gas-rich galaxies at the stellar mass given on the log $M_*$ plane (the black solid line on Figure 3). As a galaxy undergoes the gas-depletion process, $\Delta_{\text{gas}}$ decreases and moves downward in the log $M_*$ plane. When $\Delta_{\text{gas}}$ is lower than −1.07, the 2σ clipping result, the galaxy is defined as a gas-poor galaxy following the definition introduced in Section 2.3.2. We hereby define $\Delta_{\text{gas,fall}}$ as the gas content parameter of a galaxy at the time it arrived at 1.5 $R_{200}$ of the cluster for the first time.

The x axis in this figure is the time synchronized at their first pericentric passage moment at zero. It is evident that the measurements in panels (c) to (e) peak at the pericenter. At the peak, the ram pressure reaches $P_{\text{ram}}/k_B \sim 10^6$ cm$^{-3}$ K, which is two orders of magnitude larger than what it was at the time the galaxy first crossed 1.5 $R_{200}$ of the cluster halo (the vertical dotted line).

In order to estimate the efficiency of the ram pressure stripping, we compare the mass-weighted average of thermal pressures of all the cold gas cells belonging to a galaxy ($\langle P_{\text{thermal}} \rangle$) with the magnitude of the ram pressure. Assuming that galactic gas cells are in a hydrostatic state, their thermal pressure balances with the gravity at the position. Thus when the ram pressure acting on a galaxy is stronger than $\langle P_{\text{thermal}} \rangle$, the galactic gas is pushed out from the gravitational potential (see Mori & Burkert 2000; Marcolini et al. 2003; Roediger & Hensler 2005). The cold gas cells of the sample galaxy have their average thermal pressure of $\langle P_{\text{thermal}}/k_B \rangle \sim 10^{3-4}$ cm$^{-3}$ K at all times (see the blue solid line in panel (b)), so gas stripping is expected to occur ($\langle P_{\text{thermal}} \rangle < P_{\text{ram}}$) once the
galaxy falls inside roughly $R_{1.5} \approx 200$ of the cluster halo. Considering that the thermal pressure is highest at the central region of a galaxy and decreases going outward, some gas stripping can take place at the outskirts of the galaxy even earlier. We will show in Section 6.1 that the amount of stripped gas increases with the magnitude of the ram pressure, starting from $P_{\text{ram}}/k_B \sim 10^3 \text{ cm}^{-3} \text{ K}$.

Note that the time evolution of the gas content parameter in panel (b) follows the change in the ram pressure. If other environmental processes such as galaxy interactions played an important role in gas stripping, the time evolution of the gas content parameter would appear stochastic instead of smooth. This strongly suggests that ram pressure is the dominant source of gas stripping inside clusters.

We examine the fraction of galaxies that become gas poor during the first infall by measuring the time for galaxies to become gas poor ($\tau_{\text{deple}} \equiv \tau_{\text{pericentric pass}}$) and compare it with a galaxy’s first-crossing

---

**Figure 10.** Evolution of a gas-rich galaxy falling into a cluster. (a) The red dashed line is the infalling orbit, and the panels labeled from A to E show the transformation in the gas morphology. The gray circle shows the cluster region ($< R_{1.5} \approx 200$), and numbers inside brackets are the time before (negative) or after (positive) the first pericentric pass. This galaxy underwent severe gas stripping, losing the majority of its gas during the first approach to the cluster center (see also Table 1). The panels on the right show the time evolution of the (b) gas content, (c) magnitude of the ram pressure (cm$^{-3}$ K), (d) ambient medium density (cm$^{-3}$), and (e) velocity of a galaxy with respect to its ambient medium (km s$^{-1}$). The x axis is synchronized to zero at the first pericentric passage moment of the galaxies. The red dashed lines show the evolution of the example galaxy shown in panel (a), solid black lines are the median of all the galaxies, and gray shades show the 30th and 70th percentiles. The evolution of gas content of galaxies follows well the change in the ram pressure, and the strong ram pressure experienced by the example galaxy is common among our YZiCS galaxies.

| $t - t_{\text{first-peri}}$ (Gyr) | $M_{\text{gas}}$ ($M_\odot$) | $M_{\text{gas}}/M_{\text{gas, infall}}$ | $P_{\text{ram}}/k_B$ (cm$^{-3}$ K) | $\langle P_{\text{thermal}}/k_B \rangle$ (cm$^{-3}$ K) |
|---------------------|---------------------|---------------------|---------------------|---------------------|
| A Cluster infall    | -1.06               | $3.9 \times 10^9$   | 1.0                 | $5.5 \times 10^3$   | $2.3 \times 10^3$  |
| B                    | -0.49               | $1.5 \times 10^9$   | 0.375               | $2.6 \times 10^4$   | $7.8 \times 10^3$  |
| C                    | -0.24               | $5.6 \times 10^8$   | 0.141               | $7.2 \times 10^4$   | $6.9 \times 10^3$  |
| D First pericenter   | 0.0                 | $5.9 \times 10^7$   | 0.015               | $7.2 \times 10^3$   | $1.5 \times 10^4$  |
| E                    | +0.24               | 0.0                 | 0.0                 | $1.7 \times 10^3$   | –                  |

**Table 1.** Time Evolution of Gas Properties of a Sample Galaxy Displayed in Figure 10

**Note.** The first column corresponds to each snapshot marked on panel (a) of Figure 10. The columns from left to right are the (1) time before and after the pericentric pass, (2) cold gas mass, (3) cold gas mass scaled with the gas mass at the infall, (4) magnitude of the ram pressure, and (4) mean thermal pressure of the cold gas cells that belong to the galaxy.
timescale \((τ_{\text{first}} \propto t_{\text{first}} – t_{\text{pericenter}})\). In panel (a) of Figure 11, the orange symbols show the median depletion timescales of galaxies of each cluster, and the error bars are the 30th and 70th percentiles. The satellite galaxies in more massive clusters lose their cold gas faster (see the linear fit, orange dashed line); that is, the environmental effect is stronger in more massive clusters. On the contrary, the first-crossing timescale (blue symbols and error bars) is nearly constant over the range of cluster mass when stacking galaxies with various infall times, which is consistent with the simple expectation for the dynamical timescale of virialized systems \(τ_{\text{dyn}} \propto \frac{1}{\sqrt{Gρ}}\), where \(ρ\) is the overdensity of a dark matter halo, which is 200 times greater than the critical density of the universe). Panel (b) shows the fraction of galaxies that become gas poor during the first infall \(\left(τ_{\text{deple}}/τ_{\text{first}} < 1\right)\) in each cluster. As expected from panel (a), the fraction increases with increasing cluster mass. Nevertheless, a notable fraction of galaxies (\(~35\%) have their gas depleted by the first pericentric pass even in the low-mass clusters (\(<10^{14} M_\odot\)); that is, the severe gas loss found in the previous example (Figure 10 and Table 1) is not exclusive to massive cluster environments only.

5.2. What Determines the Gas-depletion Timescale in Clusters?

In this section, our aim is to answer under what conditions gas depletion is efficient (see also McCarthy et al. 2008). We base our analysis on the following three parameters representing the physical properties of infalling galaxies: gas content, stellar mass, and orbital shape.

Figure 12 shows \(τ_{\text{deple}}/τ_{\text{first}}\) depending on \(Δ_f\), and each line represents the galaxies in different \(M_\odot\) ranges. Note that we present the depletion timescales averaged in log scale as their distribution better follows a lognormal distribution, rather than a Gaussian. The most prominent trend shown here is that it takes longer for the galaxies with higher values of \(Δ_f\) to become gas poor.

At fixed \(Δ_f\), the gas depletion is slightly faster when the stellar mass of galaxies is smaller. This trend agrees with the findings on preprocessing in Section 4; that is, galaxies with lower stellar masses are more likely to become gas poor within group halos. Note that our definition of gas-poor galaxies is applied at a fixed stellar mass in order to consider the stellar mass dependence of the gas fraction. Therefore, the discrepancy in the depletion timescale between low- and high-mass galaxies can be considered as a distinction in the efficiency of the gas-depletion process in clusters.

In Figure 13, we compare the effect of \(Δ_f\) and the orbital shape on the gas-depletion timescale. As a proxy for the orbital shape, we use the first pericentric distance of galaxies.
values of $f_{\text{gas,infall}}$ have higher $M_{\text{b, before}}$ at fixed stellar mass (see the background colors in each bin). We are thus confident that it was the environmental effect in previous group halos that caused the low values of $f_{\text{gas,infall}}$ of our satellite infallers.

Combining our findings that (1) galaxies with a lower gas content at the time of their infall lose their gas faster and (2) the gas contents of satellite galaxies are lower than those of central galaxies, we understand the clear separation between the central and satellite infallers in terms of the fraction of galaxies that become gas poor during the first infall (see panel (b) of Figure 14). Generally, the satellite infallers (green) show a larger fraction of galaxies becoming gas-poor galaxies before their first pericentric pass compared with the central infallers (blue). Also, note that the slope of the linear fit is different between the two groups. In massive clusters ($>10^{14.5} M_{\odot}$), both satellite and central infallers go through the extreme environmental effect, capable of depleting their cold gas during their first approach to the center. When it comes to low-mass clusters (<$10^{14} M_{\odot}$), the environmental effect in these clusters is still sufficient to deplete the satellite infallers, but not strong enough to deplete the central infallers during their first infall. Therefore, we can say that the cluster mass dependence on the efficiency of environmental effect shown in panel (b) of Figure 11 is mainly caused by the central infallers.

5.4. Summary of Cluster Process

In this section, we discuss the violent nature of the gas depletion of galaxies falling into clusters, in particular during the first approach to the center. We also examine the effect of the physical properties of infalling galaxies, for example, stellar mass, gas fraction, and orbital shape, on the gas-depletion timescale. Generally, our galaxies significantly lose their gas (starting from the outskirts) during the first approach to the cluster center. The following is a summary of the results:

(i) The gas-depletion timescale strongly depends on the gas content of galaxies at the time of cluster entry. The larger the gas content, the longer it takes to be “gas poor.”

(ii) The orbital shape affects the gas-depletion timescale of a galaxy. The galaxies falling with a more radial orbit lose their gas faster. However, the effect of orbital shape becomes weaker when the infalling galaxy is low in gas content.

(iii) By separating the central and satellite infallers, we find a distinction between the two populations in terms of the gas content at the time they arrive at the clusters: central infallers on average have a higher gas content. We claim that the variation in gas content originates from the environmental effect in group-size halos prior to the cluster entry.

(iv) Satellite infallers (with a lower gas content) take a shorter time to become gas poor almost regardless of the cluster mass. On the contrary, central infallers (with a higher gas content) show a strong dependence on cluster mass.

5.3. What Determines the Initial Gas Content?

We have shown in the previous section that $\Delta f_{\text{gas,infall}}$ is the primary parameter that determines the gas-depletion timescale. Now, we examine the origin of its variation and its consequence.

We divided cluster-infalling galaxies into central and satellite infallers following the definitions in Section 4, that is, galaxies that have always been central galaxies before reaching clusters and galaxies that have been a satellite. In Figure 14, we found central infallers generally (blue solid contour) have larger gas contents ($f_{\text{gas,infall}}$) than satellite infallers (green solid contour) at fixed stellar mass at the time they arrive at clusters (see also Catinella et al. 2013). As introduced in Figure 3, the black solid and dashed lines represent the gas-rich galaxy sequence and the demarcation of the gas-poor galaxies, respectively. The galaxies with lower
Figure 14. (a) $1\sigma$ distribution of central (blue) and satellite (green) galaxies on the $M_{\text{infall}}$-$f_{\text{gas, infall}}$ plane. The black solid line is the gas-rich galaxy sequence at redshift zero presented in Figure 3, and the dashed line is the demarcation of the gas-poor galaxies. At a fixed stellar mass, the satellite infallers have a lower gas fraction compared to centrals at the time they first arrive at clusters. The background colors indicate the average $M_{\text{h,before}}$ before at each bin. The galaxies with lower-gas fraction tend to have higher $M_{\text{h,before}}$. (b) The fraction of galaxies that become gas deficient during their first infall as a function of the cluster mass (only the galaxies that reach their first pericentric pass by redshift zero are used). Error bars are measured as the standard error of the mean of a binomial distribution. The galaxies are separated into groups of the central (blue) and satellite infallers (green). At all clusters, the satellite infallers are more likely to become gas poor during their first infall.

Figure 15. (a) Ram pressure intensity acting on galaxies vs. their host halo mass. The bottom and top of each box are the first and third quartiles, and the whiskers show the 5th and 95th percentiles. The red and blue colors represent the satellite and central galaxies, respectively. The red diamond symbol shows the median ram pressure intensity of satellite galaxies in the inner region ($<0.3 R_{\text{vir}}$) of their host halos. Satellite galaxies always experience stronger ram pressure (especially satellites in the inner regions) compared with centrals, and the ram pressure acting on satellites becomes stronger with increasing host mass. (b) Gas stripping efficiency of galaxies, that is, the amount of gas stripped out between two snapshots divided by the initial gas mass (see Equation (4)), vs. the ram pressure intensity. The blue and orange colors indicate the less massive ($<10^{10} M_\odot$) and massive ($>10^{10} M_\odot$) galaxies, respectively. With increasing ram pressure intensity, galaxies strip their gas more efficiently between snapshots. In particular, less massive galaxies with lower gravitational restoring force lose their gas more easily than massive galaxies at a given ram pressure intensity.
6. Discussion

6.1. Ram Pressure Stripping in YZiCS Galaxies

In Section 5.1, we demonstrated that the pattern of gas stripping is well matched by the characteristics of ram pressure stripping. Here we discuss it in further detail.

Panel (a) of Figure 15 demonstrates how the magnitude of the ram pressure \( (P_{\text{ram}} = \rho_{\text{ICM}} v_{\text{rel}}^2) \) acting on galaxies varies with host halo mass. The bottom and top of each box are the first and third quartiles, and the whiskers show the 5th and 95th percentiles. Since the intensity of the ram pressure can vary significantly depending on the radial distance from the halo center, we also show the ram pressure intensity measured only with the satellite galaxies residing in the central region \( (<0.3 \, R_{200}) \) of their host halos with diamond symbols. Satellite galaxies (red) always experience stronger ram pressure compared to centrals. In particular, in massive groups \( (>10^{12} \, M_\odot) \), the ram pressure acting on the satellites in the central regions (red diamonds) is about two orders of magnitude stronger than that acting on the centrals in the same halos. As the host halo mass increases, satellite galaxies undergo stronger ram pressure because of the increased intra-group medium density and orbital velocity.

Panel (b) of Figure 15 shows the efficiency of gas stripping in YZiCS galaxies depending on the magnitude of the ram pressure. From the analytic description of ram pressure stripping by Gunn & Gott (1972), the amount of stripped gas depends on the ram pressure intensity and gravitational restoring force of a galaxy. In this paper, the stripping efficiency is measured at every snapshot as follows:

\[
\text{Stripping efficiency} = \frac{\text{Total gas loss} - \text{SF consumption}}{m_0}.
\]

\[
\text{Total gas loss} = m_0 - m_1
\]

\[
\text{SF consumption} = \sum \text{SFR} \times \Delta t,
\]

where \( m_0 \) is the gas mass of a galaxy at the previous snapshot, \( m_1 \) is the gas mass at the following snapshot, and \( \Delta t \) is the time interval between two snapshots, roughly 70 Myr. The amount of gas consumption through star formation is measured by counting the number of star particles that are created between snapshots. When estimating the amount of gas stripped from the galaxy, we assume that all of the decrease in the gas content, other than the consumption through star formation, is solely associated with this channel, because we cannot directly separate out gas elements escaping from the system in the AMR technique used in RAMSES. Star particles in our prescription expel 10% of their mass into gas 10 Myr after their formation, mimicking the mass loss through a Type II supernova explosion, but we do not consider the supply of gas through this channel for computing gas-stripping efficiency. For this reason, our stripping efficiency is a lower limit.

In isolated environments or the outskirts of halos where the ram pressure is weak \( (P_{\text{ram}}/k_B < 10^4 \, \text{cm}^{-3} \, \text{K}) \), the stripping efficiency is effectively zero (see panel (b) of Figure 15). In this case, the gas consumption through star formation dominates the mass variation in the gas reservoir, and even if there may be some amount of gas stripped out from a galaxy, the effect is easily canceled out by the gas replenishment. However, for galaxies undergoing stronger ram pressure \( (P_{\text{ram}}/k_B > 10^4 \, \text{cm}^{-3} \, \text{K}) \), we find that the efficiency of gas stripping increases with increasing ram pressure intensity.

At the same time, at a given value of ram pressure, the stripping efficiency depends on the stellar mass of a galaxy. The blue boxes in Figure 15 show low-mass galaxies \( (<10^{10} \, M_\odot) \) with a weak gravitational restoring force, and the orange boxes represent massive galaxies \( (>10^{10} \, M_\odot) \). We find that the lower mass galaxies lose more of their gas at a given ram pressure. These results agree with the findings in Section 4, that low-mass satellite galaxies associated with massive group halos have a higher chance of being gas poor.

Figure 16 shows the star and gas distributions of six YZiCS galaxies with different ram pressure intensities selected from different redshift ranges. The galaxies in the upper row are experiencing gas stripping within the cluster halo, while the bottom row shows the galaxies that are undergoing group preprocessing outside clusters. The yellow contour shows the gas column density distribution separated by 0.4 dex in log scale. In all panels, even in the panels showing galaxies in group-size halos, the stripped gas tails extend along the ram pressure wind-blowing direction (cyan arrow). Despite the severe deformation of the gas morphology, the stellar distributions remain unaffected. These features are direct evidence of the ram pressure stripping often observed in cluster galaxies (Chung et al. 2007, 2009; Abramson et al. 2011).

In Section 5.1, we discussed the efficiency of ram pressure stripping by comparing the magnitude of the ram pressure and the mean thermal pressure of galactic gas \( (P_{\text{thermal}}) \) that correlates with the gravitational restoring force, in each galaxy. When considering the spatial variation of thermal pressure of galactic gas within a galaxy, even the galaxies undergoing strong ram pressure usually have gas cells whose thermal pressure is larger than the ram pressure in action in their central region (the green contour). These cells \( (P_{\text{thermal}} > P_{\text{ram}}) \) can be considered a “safe zone” against ram pressure stripping.

We find in our simulation that ram pressure stripping is at work in groups as well as in clusters. However, discovery of galaxies with a disturbed gas morphology has been rare in group environments, which might appear to contradict our result. We can understand this by inspecting the magnitudes of the ram pressure that typical galaxies in groups and clusters experience. Panel (a) of Figure 15 shows that the difference in ram pressure between the satellites in the central regions (red diamonds) of groups (e.g., \( 12.2 < \log M_{\text{host}}/M_\odot < 13 \)) and clusters \( (13.8 < \log M_{\text{host}}/M_\odot) \) is a factor of 40 \( (\log P_{\text{ram}}/k_B \sim 3.75 \, \text{cm}^{-3} \, \text{K}) \) for group satellites and \( \sim 5.35 \) for cluster satellites. Thus, ram pressure stripping in groups is much more difficult to detect at any specific moment of observation. In fact, the most disturbed group satellite sample in Figure 16 (bottom left panel) shows an extremely rare case with a high ram pressure. Despite that, the cumulative amount of ram pressure stripping in groups is significant simply because it accumulates typically for more than a few gigayears before galaxies fall into a large cluster, whereas the typical cluster-processing timescale is only about 1 Gyr.

6.2. Caveats

The resolution of our simulation does not resolve detailed features of the Kelvin–Helmholtz instability at the interface between the galactic gas and the ICM, and thus it is likely to underestimate gas loss in satellite galaxies (e.g., Nulsen 1982; Roediger & Hensler 2005; Roediger & Brüggen 2007). However, compared with the observational references introduced in Section 1
that galaxies keep forming stars for several gigayears after entering the clusters, YZiCS galaxies seem to lose too much of their cold gas and terminate their star formation too quickly even without continuous stripping. Here, we discuss possible origins for this disparity.

First, although our simulations adopt a spatial resolution (~ $h_0^{-0.76}$ kpc) comparable to the current state-of-the-art cosmological simulations, such as Horizon-AGN (Dubois et al. 2014), Illustris (Vogelsberger et al. 2014), or Eagle (Schaye et al. 2015), it is still not sufficient to resolve the detailed structure of the multiphase ISM. For example, using the solar neighborhood conditions for star formation and radiation field, Kim et al. (2013) showed that the total pressure in a cold and dense medium can be as high as $P_{\text{thermal}} \approx 10^{-4}$ cm$^{-3}$ K (see also Kimm et al. 2018 for a gas-rich, dwarf galaxy environment). The pressure can increase even further if infrared dark clouds ($n_{\text{H}_2} > 10^4$ cm$^{-3}$) are concerned, suggesting that star-forming regions are likely to be resilient to the ram pressure stripping in group/cluster environments (i.e. $P_{\text{ram}}/k_B \gtrsim 10^{-4.5}$ cm$^{-3}$ K). Indeed, by observing 40 Virgo spiral galaxies, Kenney & Young (1989) reported that cluster galaxies are not as much deficient in H$_2$ as in H I. Similarly, with spatially resolved observations, Vollmer et al. (2012) discovered an increased value of H$_2$ to total gas fraction on the ram pressure windward side of the galactic gas disk. On the other hand, we find that the pressure of cold gas in our simulated galaxies is $P_{\text{thermal}}/k_B \sim 10^4$ cm$^{-3}$, as the dense structures are artificially smoothed out due to a finite resolution. In this regard, it is possible that the effect of ram pressure stripping is overestimated and that star formation is overly quenched in our simulations.

The absence of magnetic fields is another issue. Ryu et al. (2000) and Hennebelle (2013) demonstrated that the Kelvin–Helmholtz instability may be suppressed in small-scale filaments if strong magnetic tension is present. Since instabilities can accelerate the stripping process, we speculate that the neglect of magnetic fields in our simulations may also have resulted in too-efficient gas stripping. At the same time, using a set of numerical simulations of a Milky Way–like disk, Tonnesen & Stone (2014) found that the gas initially pushed away from the midplane of the disk by the ICM wind can fall back more efficiently in the case with stronger magnetic tension. Interestingly, they find that the stripping rate in the simulations with different magnetic field strengths becomes eventually comparable (see Ruszkowski et al. 2014), perhaps because strong magnetic pressure leads to a thicker disk, which in turn makes the low-density gas easier to be removed from the

Figure 16. Distribution of star particles (background color) and gas column density (yellow contour) on the projected plane for six example galaxies in a different level of ram pressure at different redshift. Each contour line is separated by 0.4 dex in log density, and the dashed line corresponds to the minimum level presented in the bottom right of each panel. Galaxies in the upper panels are selected among the galaxies inside clusters, and the bottom panels show the group galaxies outside clusters. The white bar indicates the 10 kpc length scale. The pink and blue arrows indicate the direction to the host halo center and the wind-blowing direction, that is, the opposite direction to a galaxy’s motion relative to the ambient medium, respectively. The diffuse gas components extend toward the wind-blowing direction, while the stellar components remain unaffected. The green region shows the distribution of “ram pressure stripping safe” cells, that is, gas cells with a thermal pressure higher than the ram pressure acting on the galaxy ($P_{\text{thermal}} > P_{\text{ram}}$). These cells reside at the central region of the galaxies.

The Astrophysical Journal, 865:156 (18pp), 2018 October 1
Jung et al.
galaxy. However, their resolution (159 pc) may not be enough to resolve the disk scale height, and more importantly, given that their simulations do not include radiative cooling, the thickness of the galactic disk may be overestimated (e.g., Kim et al. 2013), possibly artificially enhancing the stripping rate. Thus, high-resolution magnetohydrodynamic simulations with radiative cooling will be needed to make a firm conclusion on the impact of magnetic fields on ram pressure stripping.

7. Conclusion: Three Channels for Producing Gas-poor Galaxies

Throughout this paper, we have discussed how galaxies lose their gas and become gas poor in and outside the clusters by monitoring the gas content of 3818 galaxies from our 16 YZiCS clusters. We will now combine the discussions of the previous sections to describe the overall picture of the channels producing gas-poor galaxies now found inside clusters.

Among the variety of gas-depletion histories of our galaxies, we classify the cluster galaxies that are currently gas deficient into three groups based on where and when their gas depletion occurred. First, “preprocessed” galaxies are those that became gas poor already in group-size halos before the cluster entry. Second, “fast cluster-processed” galaxies are quickly depleted in their cold gas inside clusters during the first infall. Third, the “slow cluster processing” channel is for the galaxies that retain cold gas for several gigayears after they arrive at the clusters even beyond their first pericentric pass. We summarize our understanding on each channel below and provide a schematic diagram of the possible scenarios in Figure 16.

First, “preprocessing” is efficient for the low-mass satellite galaxies in massive halos. More massive group halos have a higher intragroup medium density and higher velocity dispersion among satellite galaxies, resulting in a stronger ram pressure acting on their satellites. Meanwhile, under the given intensity of ram pressure, low-mass galaxies lose their gas more efficiently as their gravitational restoring force is small. The magnitude of ram pressure in group-size halos (\(\sim 10^{12} M_\odot\)) is enough to induce cold gas stripping. Some group satellite galaxies undergoing ram pressure stripping show a disturbed gas morphology extending toward the opposite direction of the motion. In our simulation, once satellite galaxies exhaust their gas (i.e., less than 10% of normal galaxies), they are rarely replenished in cold gas in group environments. More massive clusters are likely to accrete higher fractions of preprocessed galaxies since they usually develop in overdense regions that have higher chances of attracting massive groups. The typical pattern of the gas loss history of such galaxies is shown as “A” in the inset of Figure 16.

Second, “fast cluster processing” takes place mainly but not exclusively on the galaxies that arrive at a cluster with a small amount of gas. They are usually those that have been a satellite galaxy before the cluster entry. In this case, other details such as stellar mass, orbital shape, or cluster mass are only of secondary importance. In the case of galaxies arriving at a cluster with a significant amount of gas, if they take the radial orbit toward the cluster center or fall into an extremely massive cluster (\(\sim 10^{14.5} M_\odot\)), they may run out of their gas through the first pericentric pass, too. The typical pattern of the gas-loss history of such galaxies is shown as “B” in the inset of Figure 16.

Lastly, there is “slow cluster processing.” Galaxies that have always been a central galaxy are generally gas rich at the time they enter clusters. When a gas-rich galaxy arrives at a low-mass cluster (\(< 10^{12} M_\odot\)) and takes a circular orbit that does not approach the cluster center closely enough, the galaxy loses its gas very slowly. The typical pattern of the gas loss history of such galaxies is shown as “C” in the inset of Figure 17.

The relative importance of these channels is presented in Table 2. At redshift zero, 1922 of our YZiCS galaxies reside within 1 \(R_{200}\) of each cluster and are gas deficient. Tracing back their gas content, we find that 33.7% and 42.7% take the pre-processing and fast cluster processing channels, respectively, and the rest, 23.7%, are depleted in gas after their first pericentric pass (see the first column).

However, taking the numbers from the total galaxy sample blindly can lead us to a biased conclusion as more massive clusters own a larger number of satellites and therefore contribute more to the sample. Also, note that the YZiCS clusters are arbitrarily selected halos from a 200 Mpc \(h^{-1}\)-size cube. Therefore, to avoid the sampling bias, we weight our 16 clusters using the analytic halo mass function (MF; Tinker et al. 2008) and then calculate the weighted average (see columns (2) to (5) in Table 2). The contribution of the slow cluster processing has notably been increased mainly by the consideration of low-mass halos (second column). Separating our clusters into low (13.5 < \(log M_{\text{cluster}}/M_\odot\) < 14, third column), intermediate (14 < \(log M_{\text{cluster}}/M_\odot\) < 14.5, fourth column), and high (14.5 < \(log M_{\text{cluster}}/M_\odot\) < 15, fifth column) mass ranges, we discover that the contribution of each channel varies with the mass of the cluster. In low-mass clusters where the cluster environmental effect is relatively weak, the majority of their satellites contain gas by the time they pass their first pericenter (slow cluster processing). However, in massive clusters, the contribution of the slow cluster processing diminishes, and most of the currently gas-poor cluster galaxies were produced during their first approach to the cluster center (fast cluster processing).

With increasing cluster halo mass, we also find that a higher fraction of satellite galaxies was already gas deficient before they arrive at the current cluster (preprocessing).

Using the 16 clusters from YZiCS, we traced the gas-depletion history of individual galaxies and investigated possible channels that produce gas-poor galaxies that are current members of clusters. As often regarded in previous studies, clusters are the harshest environments in the universe, and the majority of their gas-poor members were produced after those galaxies met current clusters. However, a non-negligible fraction of galaxies was gas deficient, even before the cluster infall, that is, preprocessed.

In previous studies, pre-processing and the cluster environmental effect have been studied separately, even though these two processes always act consecutively in the evolution of a galaxy falling into a cluster. According to our simulations, galaxies have a variety of gas fractions when they first arrive at clusters. We find that the previous environmental history is an important factor that determines the gas fraction. As a consequence, whether a galaxy goes through preprocessing, fast cluster processing, or slow cluster processing channels predominantly depend on the degree of the group environmental effect that the galaxy went through before entering the cluster.

We thank Hyein Yoon and Sree Oh for the constructive feedback. S.K.Y. acknowledges support from the Korean National Research Foundation (NRF-2017R1A2A05001116). This study...
was performed under the umbrella of the joint collaboration between Yonsei University Observatory and the Korean Astronomy and Space Science Institute. The supercomputing time for the numerical simulation was kindly provided by KISTI (KSC-2014-G2-003), and large data transfer was supported by KREONET, which is managed and operated by KISTI.

ORCID iDs
Seoyoung L. Jung @ https://orcid.org/0000-0001-5512-3735
Hoseung Choi @ https://orcid.org/0000-0001-7229-0033
O. Ivy Wong @ https://orcid.org/0000-0003-4264-3509
Taysun Kimm @ https://orcid.org/0000-0002-3950-3997
Aeree Chung @ https://orcid.org/0000-0003-1440-8552
Sukyoung K. Yi @ https://orcid.org/0000-0002-4556-2619

References
Abramson, A., Kenney, J. D. P., Crowl, H. H., et al. 2011, AJ, 141, 164
Aubert, D., Pichon, C., & Colombi, S. 2004, MNRAS, 352, 376
Bahé, Y. M., McCarthy, I. G., Balogh, M. L., & Font, A. S. 2013, MNRAS, 430, 3017
Baldry, I. K., Balogh, M. L., Bower, R. G., et al. 2006, MNRAS, 373, 469
Baldry, I. K., Glazebrook, K., Brinkmann, J., et al. 2004, ApJ, 600, 681
Balogh, M. L., Baldry, I. K., Nichol, R., et al. 2004, ApJL, 615, L101
