1. Introduction

All galaxies, including the Milky Way, suffer from gravitational and hydrodynamic effects of the external environment. Strong environmental effects remove the hot and cold gases, as well as stellar outer disks, which leads to the cessation of star formation and an aging stellar population. With little input of the dynamically cold, young stars, disks suffering from the continuous heating from the external perturbations undergo morphological transformation. Galaxy evolution is hence accelerated by these effects. Massive clusters provide an ideal laboratory to study a variety of environmental effects, particularly the ram pressure stripping process.

Gunn et al. (1972) provided the first analytical model of RPS, in which the interstellar gas of a galaxy gets stripped if the ram pressure is higher than the anchor force. In this model, the ram pressure depends on the density of the intra-cluster medium (ICM) and the velocity of the galaxy, and the anchor force depends on the surface density of the ISM and the internal gravity on it in the direction perpendicular to the disk. Later hydrodynamic simulations found that RPS is stronger for face-on infalling galaxies than for edge-on ones (Roediger & Brüggen 2006; Jáchym et al. 2009), and the orbits of infall affect the cumulative effect of RPS (Tonnesen 2019). Pressures from the hot gas halo help to constrain the interstellar gas against the ram pressure (Steven & Brown 2017; Cora et al. 2018), though a significant fraction of the galaxies should have lost the hot gas halo and start strangulation (Larsen et al. 1980) during an early stage of the infall (Bekki 2009; Bahé et al. 2013). Some of the interstellar gases stripped off the disk plane may be accreted later if they do not reach the escape velocity (Vollmer et al. 2001). Despite these uncertainties, the model of Gunn et al. (1972) is a good approximation to quantify the strength of RPS. It is widely applied in semi-analytical models (SAMs) of galaxy evolution with RPS (Gonzalez-Perez et al. 2014; Henriques et al. 2015; Luo et al. 2016; Stevens & Brown 2017; Cora et al. 2018; Lotz et al. 2019) and is used to interpret observational trends. Based on the Gunn et al. (1972) model, we expect RPS to be most effective in the core region of massive clusters and on the low-mass galaxies.

Observations confirmed RPS as one effective mechanism in the evolution of both individual galaxies and the general star-forming population near the cores of clusters. Galaxies under RPS were identified in nearby clusters, with a truncated edge on the leading side and a tail on the trailing side of infalling gas disks (e.g., Chung et al. 2009; Abramson et al. 2011; Boselli et al. 2016; Yagi et al. 2017; Gavazzi et al. 2018). These galaxies typically show high HI deficiency, which is indicative of a recent gas removal and future quenching of star formation (Cayatte et al. 1994; Bravo-Alfaro et al. 2000; Chung et al. 2009; Boselli et al. 2016). They represent a subset of the galaxies under strong RPS because the observability of tails can depend on both the observing angle and the thermal pressure of the ICM (Tonnesen & Bryan 2010). The averaged behavior of galaxies in clusters also supports the importance of RPS. Both the gas mass and star formation rate (SFR) of galaxies at a given stellar mass decrease on average toward the cluster centers (Hess & Wilcots 2013; Woo et al. 2013; Odek et al. 2016; Brown et al. 2017). These trends are more prominent for low-mass galaxies than for high-mass galaxies (Cortese et al. 2011; Zhang et al. 2013), and in more massive halos than in less massive halos (Odek et al. 2016; Brown et al. 2017). The interstellar medium and SFR show an averaged behavior of outside-in shrinking within galaxies near the core of clusters: when compared to the field galaxies, the most extended component HI shows the strongest deficiency, the less extended dust, molecular gas and integral SFR are also reduced but to a less extent, and the inner most central SFR is the least affected (Crowl et al. 2005; Boselli et al. 2006; Cortese et al. 2010; Boselli et al. 2014a; Mok et al. 2017; Boselli et al. 2020). These trends are qualitatively consistent with the way that RPS is predicted to work and they indicate the dominating role of RPS near the core of clusters.

The relative importance of RPS among many other environmental effects is less clear in the outer region (i.e., near and beyond the virial radius) of clusters (Koopmann & Kenney 2004a). Galactic tidal stripping and mergers are expected and observed to be relatively frequent there (Chung et al. 2009) because the galaxy densities are higher than in the field but the relative velocities of galaxies are not as high as those near the cluster cores (Boselli et al. 2006). Strangulation...
due to removal of the hot gas halo is also expected to happen at much larger cluster-centric distance than RPS of the cold gas (Larson et al. 1980; McCarthy et al. 2008; Bahé et al. 2013). There is still no consensus on how the star formation activity of galaxies is reduced through the clusters. A slow+fast declining mode is derived by several authors (Muzzin et al. 2012; Wetzel et al. 2012; Wijesinghe et al. 2012; Wetzel et al. 2013); others rather indicate a slow decline (McGee et al. 2009; Wolf et al. 2009; von der Linden et al. 2010; Paccagnella et al. 2016), while others suggest a rapid quenching (Boselli et al. 2016; Oman & Hudson 2016). While these debates may be partly attributed to biases in sample selection or analysis methods, they suggest a complexity in environmental effects. The galaxies with a fast declining SFR are usually associated with strong RPS, which can theoretically remove 70% of the cold gas in a few hundreds Myrs (Yun et al. 2019); while those with a slowly declining SFR may be under a mixture of effects including weak RPS. Some insights about the relative role of RPS could be gained from cosmological simulations; however, due to the complex nature of galaxies, properly modeling the HI and SFR of central and satellite galaxies in clusters has been difficult (Gonzalez-Perez et al. 2014; Henriques et al. 2015; Luo et al. 2016; Stevens & Brown 2017; Cora et al. 2018; Lotz et al. 2019; Stevens et al. 2019). More observational inputs may help constrain the simulations. One way of better separating the effect of RPS in observations is to derive model motivated parameters. The ram pressure and the anchor force in the Gunn et al. (1972) model can be roughly estimated from observations in X-ray, optical, and HI or ionized gas. Studies based on the IFU survey of Jellyfish galaxies, GASP (Poggianti et al. 2017), found that the observed significance of RPS tails in the ionized gas are consistent with the levels of ram pressures in comparison to anchor forces (Jaffé et al. 2018). Another useful tool is the projected phase-space diagram (PSD), which is a plot of the radial velocities as a function of the projected cluster-centric distances that effectively traces the infall stage of galaxies (Mahajan et al. 2011; Oman et al. 2013; Oman & Hudson 2016; Rhee et al. 2017). By requiring the ram pressure to be larger than the anchor force at all galactic radii, a “stripping region” of HI, where galaxies are undetected in shallow HI surveys, was successfully predicted on the projected PSD for several massive clusters (Jaffé et al. 2015, 2016; Yoon et al. 2017). Studies based on high-resolution HI images show HI richness consistent with infall stages indicated by the projected PSD positions, but the galaxies displaying RPS tails are typically found beyond the stripping regions (Yoon et al. 2017), which is reasonable as the RPS timescale in the stripping region is short (a few tens of Myr, Abadi et al. 1999).

HI is an excellent tracer of the relatively early stage of environmental processing on star-forming galaxies. It is the reservoir for forming stars and it is sensitive to perturbations when it is more extended than the stellar disks. Thus, its richness is associated with both the strength of environmental effects and the progress of star formation cessation (Boselli et al. 2006; Boselli & Gavazzi 2014). High-resolution interferometric images for selected galaxies in nearby clusters, particularly in Virgo, have revealed the morphological and kinematic features of HI in galaxies in response to RPS and other environmental processes (Chung et al. 2009; Yoon et al. 2017). They provide valuable constraints to zoom-in simulations modeling physical details of the RPS process (e.g., Tonnesen & Bryan 2009). Low-resolution (usually single-dish) but blind and contiguous HI surveys provide opportunities to completely map a cluster out to several times the virial radius, and cover statistically significant number of clusters and galaxies (Jaffé et al. 2015, 2016; Haynes et al. 2018). Studies based on this type of data characterize the statistical behavior of galaxies when they are potentially affected by RPS (Hess & Wilcots 2013; Yoon & Rosenberg 2015; Odekon et al. 2016). These statistical observational results help to constrain simulations under a cosmological context, focusing on the role that RPS plays among many other processes in the general evolution of galaxies (e.g., Stevens et al. 2019; Yun et al. 2019).

A major limitation of the blind HI surveys is the low resolution, while RPS is predicted to be dependent on the HI surface density at a given radius in the galaxies (Gunn et al. 1972). Hence, predicting the HI radial distribution based on rules extracted from the interferometry data of nearby galaxies will provide some insights when one attempts to link the observed total HI mass to the RPS process. Such an analysis has often been used in statistical studies with low-resolution HI data on the topic of RPS (Boselli et al. 2014b; Jaffé et al. 2015, 2016; Boselli et al. 2018). Exploring methods to enhance the science value of low-resolution HI data is also in line with a preparation for SKA pathfinder HI surveys, for the number of new HI detections will explode but the majority of them will be unresolved in these surveys (Staveley-Smith & Oosterloo 2015).

Recent advances in observations enable us to predict HI radial profiles with higher accuracy than before. Based on HI images for over 500 nearby galaxies, Wang et al. (2016) found that all these galaxies lie tightly on a relation between the HI mass and a characteristic radius of the HI disks ($R_{HI}$), the relation partly arises because the outer region of HI disks have similar radial profiles when the radius is normalized by $R_{HI}$ (also see Wang et al. 2014). The similarities seem to be a result from the sophisticated balance between different physical processes, including the accretion, radial flow, and depletion of the HI (Wang et al. 2014; Bahé et al. 2016). Using the median HI radial profile (normalized by $R_{HI}$) from Wang et al. (2016), Wang et al. (2020) showed that the HI mass beyond and within the optical radius of galaxies can be predicted to a high accuracy. Because the majority of the galaxies from the Virgo cluster lie on the same HI size-mass relation, and exhibit a similar median HI radial profile as the field galaxies (Wang et al. 2016), we may also use these characteristics to predict the HI radial profile of galaxies in clusters for statistical studies of RPS.

In this paper, we combine the Gunn et al. (1972) model with the projected PSD, and conduct a statistical analysis of RPS effects on HI-detected galaxies beyond the stripping regions of X-ray detected, massive clusters. We modify the classical way of estimating the anchor forces, by better predicting the HI distribution in individual galaxies. Compared to many earlier studies which characterized the relatively strong type of RPS with galaxies showing significant HI deficiencies, we more closely focus on a relatively early stage of RPS that is weak and has not yet strongly depleted the HI or suppressed the SFR of galaxies. We attempt to evaluate the statistical significance of weak RPS among the HI-rich population falling into clusters.

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4 The gas is assumed to be distributed exponentially in the multi-zone chemically spectrophotometric model of Boselli et al. (2018, 2014b).
particularly in the cluster outer regions where many environmental effects co-exist. We ask at what cluster-centric radius does RPS occur in the selected clusters? What is the fraction of HI-rich galaxies affected by RPS at each cluster-centric distance? And, how different are the galaxies under relatively weak RPS from the field galaxies with similar integral SFR? We present the sample selection in Section 2.1, and we give the estimate of the RPS strengths in Section 3. We present the results in Section 4, we give our discussion in Section 5, and we conclude in Section 6. Throughout this paper, we assume a Chabrier initial mass function (Chabrier 2003), and a $\Lambda$CDM cosmology with $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$ and $h = 0.7$. We do not account for the contribution of helium when discussing HI properties, unless specified.

2. Data

2.1. X-Ray Detected Clusters

2.1.1. The HIFLUGCS and RXGCG Samples

We use two X-ray samples of nearby clusters, the HiHighest X-ray FLUx Galaxy Cluster Sample (HIFLUGCS, Reiprich & Böhringer 2002) and RASS-based extended X-ray Galaxy Cluster Catalog (RXGCC, Xu et al. in prep).

HIFLUGCS selected from the ROSAT All-Sky Survey (RASS) the 63 brightest clusters, with Galactic latitude $|b_{HI}| > 20^\circ$, and outside the LMC, SMC, and Virgo regions. Reiprich & Böhringer (2002) fit beta models to the X-ray surface brightness profiles of the high-mass clusters

$$S(r) = S(0)(1 + r^2/r_c^2)^{-3/2}$$

where $S(r)$ is the surface brightness at radius $r$. Assuming the ICMM to be in hydrostatic equilibrium and isothermal, they derived $R_{200}$ based on the best-fit X-ray surface brightness models, where $R_{200}$ is the radius within which the averaged mass density is 200 times the critical cosmic matter density at the redshift. Their assumption of ICM status ignored the local dynamics, but provides reasonable description for large-scale properties like $R_{500}$. The HIFLUGCS clusters have been extensively studied in the literature, including their detailed ICMM distributions (Eckert et al. 2011).

RXGCC used a state-of-art algorithm, which includes the wavelet filtering, source extraction and maximum likelihood fitting, to extract from X-ray images the low surface density groups or clusters, and built a sample of 764 clusters and groups from RASS (Xu et al. 2018, Xu et al. in prep). In Xu et al. (2018), the $R_{500}$ is obtained from the appearance of galaxy clusters and the significance radius, which is derived from the growth-curve analysis. They further derived $R_{200} \approx 1.538R_{500}$ assuming NFW profiles with a concentration index of 4. The RXGCC optimized the measurements for the faint clusters and groups, and is complementary to the HIFLUGCS sample.

We select clusters with redshift $z < 0.05$ to match the ALFALFA redshift range, and are left with 45 and 207 clusters in HIFLUGCS and RXGCC. The $M_{200}$ distribution of HIFLUGCS after the redshift selection has 20, 50 and 80 percentiles of 1.63, 4.52 and 6.73 $\times 10^{14} M_\odot$, and for RXGCC the percentiles are 0.42, 0.89 and 1.84 $\times 10^{14} M_\odot$. We select clusters with $M_{500} > 2 \times 10^{14} M_\odot$ and $<2 \times 10^{14} M_\odot$ from HIFLUGCS and RXGCC, respectively, and are left with 37 and 170 clusters in each sample. We call the subsamples out of HIFLUGCS and RXGCC the high-mass and low-mass cluster samples respectively in the following analysis. Despite the relative difference in mass, both types of clusters are massive clusters compared to optically selected groups, as suggested by the detection in the X-ray.

2.1.2. Parameters that Define the Cluster Region

In the next section, we select member galaxies of the clusters based on the distribution of galaxies on the projected PSD of radial velocity difference as a function of projected cluster-centric distance.

We first derive the relation of the escape velocity ($v_{esc}$) as a function cluster-centric distance ($d$), assuming an NFW–Frenk and White (NFW, Navarro et al. 1997) profile for the dark matter distribution. We assume for the NFW profiles a concentration index of 4. Because of projection effects, we replace $d$ with the averaged, projected cluster-centric distance $d_{proj} \approx \pi/4d$, and because only radial velocities are observable, we replace $v_{esc}$ with the averaged, radial escape velocity $v_{esc} \sim v_{esc,0}/\sqrt{3}$. The $v_{esc}$-$d_{proj}$ relation has been proven to be effective in identifying infalling and settled galaxies of clusters (Oman et al. 2013).

In this paper, a galaxy is identified as a (settled or infalling) member of a cluster if $d_{proj} < 2R_{200}$, and the radial velocity difference $|\Delta v_{rad}|$ is smaller than the value of $v_{esc}$ expected at $d_{proj}$.

2.2. HI-detected Galaxies

2.2.1. Selection from ALFALFA, MPA/JHU Catalog, and GSWLC-2

ALFALFA (Haynes et al. 2018) mapped 7000 deg$^2$ in the southern sky with a typical rms of 1.6 mJy at a channel width of 18 km s$^{-1}$ (after smoothing). The angular resolution (beam size) is 3.5 arcmin in full-width half-maximum. ALFALFA provided each detected galaxy the integral HI mass, $M_{HI}$. We estimate the characteristic radius $R_{HI}$, based on the HI size-mass relation (Wang et al. 2016), where $R_{HI}$ is the semimajor axis of the $1M_\odot$ pc$^{-2}$ isophote of HI disks. The ALFALFA catalog has assigned each HI detection an optical counterpart from SDSS or DSS, based on the projected distance, redshift, color, morphology, and additional scientific judgment from its authors (Haynes et al. 2011). We will use the optical coordinates of the ALFALFA detected galaxies in cross-matching with other galaxy catalogs.

The MPA/JHU catalog (Kaufmann et al. 2003) provides spectroscopic measurements of galaxies from Data Release 7 of SDSS (Abazajian et al. 2009). We will use the spectral indices $D_{4000}$, and equivalent width of the H\textalpha emission ($EW(H\alpha$), positive values for emissions here) to indicate the star-forming status in the galactic center. $D_{4000}$ is produced mainly because spectrum to the blue side of 4000 Å is strongly absorbed by metals in the atmosphere of old stars. So low values of $D_{4000}$ suggest existence of a significant amount of young stellar population. $H\alpha$ emission is produced by ionizing radiation from O stars with a typical life time of 10 Myr. We also use the photometric measurements of $g$-band $R_{25}$ (semimajor axis of the 25 mag arcsec$^{-2}$ isophote), $i$-band $R_{50}$ (half-light radius), and $r$-band $R_{90}$ (90%-light radius), $R_{50}$ and $R_d$ (the scale-length). We calculate $\mu_4$, the averaged stellar surface density within the $i$-band $R_{50}$, and the concentration index $R_{90}/R_{50}$ in the $r$-band.
The GALEX–SDSS–WISE Legacy Catalog 2 (GSWLCL-2, Salim et al. 2016) selected galaxies overlapping in GALEX (Martin et al. 2005), SDSS and WISE (Wright et al. 2010). It estimated the integral SFR and stellar mass ($M_{\ast}$) of galaxies by fitting stellar synthesis models to the broad-band spectral energy distribution ranging from the mid-infrared to the far-ultraviolet. The SFRs are mainly indicated by the attenuation corrected ultraviolet light, with sensitivity on a timescale of $\sim$100 Myr.

We first search for member galaxies of each cluster from the ALFA catalog, using the criteria based on $R_{200}$ and $v_{esc}$. We then match the optical coordinates of the ALFA detected galaxies to the MPA/JHU catalog, and then to GSWLC-2, by requiring the projected distance to be less than 3 arcsec, and the radial velocity difference less than 200 km s$^{-1}$. These cross-matching result in 158 and 144 galaxies in high- and low-mass clusters. We note that the sample size is much smaller than a few previous studies on ALFA and SDSS detected galaxies in X-ray clusters (e.g., Odekon et al. 2016), mostly because of our selection by $v_{esc}$ instead of using group catalogs built with friend-of-friend member finders (e.g., Yang et al. 2007).

Motivated by the previous results that environmental effects on gas content and SFRs are most significant in low-mass galaxies (Gavazzi et al. 2010; Catinella et al. 2013; Wetzel et al. 2013; Boselli et al. 2014b; Boselli & Gavazzi 2014; Woo et al. 2017), we select the galaxies with log $M_{\ast}/M_{\odot}$ < 11. To focus on the HI-rich galaxies under active environmental processing instead of already being fully processed, we further limit the sample to galaxies with $R_{HI}$ > $R_{25}$. By this selection, we focus on RPS of the HI gas and may miss galaxies which have little HI but the ionized gas still being stripped by the ram pressure (e.g., NGC 4569 in the Virgo cluster, Chung et al. 2009; Boselli et al. 2018).

These selection criteria reduce the sample to 142 and 128 galaxies in the high and low-mass clusters, which we refer to as the cluster sample.

2.2.2. The Control Sample and Final Main Sample

We first built a pool of all galaxies with redshift below 0.05 and detected simultaneously in the ALFA, MPA/JHU and GWSLCL-2 catalogs, which includes 13273 galaxies. For each galaxy in the cluster sample, we randomly select eight control galaxies with replacement from the galaxy pool, with $M_{\ast}$, SFR, $\mu_{\ast}$ and $z$ differing by less than 0.15 dex, 0.2 dex, 0.25 dex and 0.002, respectively. We require each galaxy from the cluster sample to have at least five unique control galaxies, which reduces the sample to 134 and 109 galaxies for the high- and low-mass clusters, This is our final, main sample of galaxies. We show their distributions in the diagrams of SFR, $M_{HI}$, and $\mu_{\ast}$ versus $M_{\ast}$ (Figure 1). They are by selection strongly biased toward the HI-rich, star-forming, low surface density population, and do not represent the general galaxy population in clusters, which are on average older and gas poorer than the field galaxies. These galaxies are useful when searching for signatures of the relatively early and weak environmental processing prevalent in the relatively outer region of clusters, which may just start to deviate galaxies from the parameter space of unperturbed galaxies. They are, however, highly incomplete when studying the relatively strong environment effects (including strong RPS), which can quick move galaxies below the detection limit of ALFA.

These galaxies are from seven high-mass clusters and 19 low-mass clusters. We list the properties of these clusters, including the number of selected galaxies from each cluster, in Table 1. Among the galaxies from high-mass clusters, 43% of them come from the Coma cluster, another 49% come from A1367, A2147 and MKW8, and the rest from the remaining three clusters. For low-mass clusters, the galaxies are more evenly contributed by each cluster, with a median number of five per cluster.

3. Analysis

3.1. ICM Density and Ram Pressure

The RPS strength of the ICM is calculated as $\rho (\Delta v)^2$, where $\rho$ is the mass density of the ICM and $\Delta v$ is the relative velocity between the ICM and the galaxy.

The density distribution of an isothermal ICM is related to the beta model of the X-ray surface brightness according to

$$\rho(r) = \rho(0)(1 + r^2/r_c^2)^{-3\beta/2}. \quad (2)$$

$r_c$ and $\beta$ are the same as the model of the X-ray surface brightness, and $\rho(0)$ can be derived by integrating the profile out to $R_{500}$, and comparing the result with the gas mass ($M_{gas,500}$) expected from scaling relations. We can use the scaling relation from Ettori (2015) to estimate $M_{gas,500}$ from $M_{500}$, the mass within $R_{500}$. So the key parameters needed are $R_{500}$ and the parameters of the beta model ($\beta$ and $r_c$), which are

![Figure 1. Scaling relations of selected cluster galaxies. From left to right, we plot the relations of SFR, $M_{HI}$ and $\mu_{\ast}$ as a function of $M_{\ast}$ for galaxies in low-mass (cyan) and high-mass (orange) clusters. The xGASS (Catinella et al. 2018) sample of $M_{\ast}$ and $z$ selected galaxies are plotted in gray as a reference. The upper limits of $M_{HI}$ in the xGASS sample are plotted as vertical bars.](image-url)
| Name   | N_gal | R.A. (deg) | decl. (deg) | Redshift | M_200 (10^{14} M_☉) | R_200 (Mpc) | R_500 (Mpc) | σ_200 (km s^{-1}) | β | μ_0 (cm^{-3}) | Π_200 (cm^{-3}) | r_e (kpc) | r_e2 (kpc) |
|--------|-------|------------|-------------|----------|----------------------|-------------|-------------|------------------|----|----------------|----------------|-----------|-----------|
| A1367  | 26    | 176.1903   | 19.7030     | 0.022    | 3.95                 | 1.49        | 0.95        | 633.9            | 0.62 | 0.0011         | ...             | ...       | ...       |
| A2052  | 6     | 229.1846   | 7.0211      | 0.035    | 2.15                 | 1.22        | 0.87        | 516.8            | 0.75 | 0.0016         | 0.0250         | 159       | 32        |
| A2063  | 5     | 230.7734   | 8.6112      | 0.035    | 3.15                 | 1.38        | 0.97        | 587.5            | 0.73 | 0.0018         | 0.0064         | 194       | 54        |
| A2147  | 24    | 240.5268   | 15.9586     | 0.035    | 3.36                 | 1.41        | 1.00        | 600.3            | 0.37 | 0.0022         | ...             | ...       | 61        |
| COMA   | 58    | 194.9468   | 27.9398     | 0.023    | 13.46                | 2.24        | 1.51        | 956.9            | 0.65 | 0.0034         | ...             | ...       | 249       |
| MKW3   | 1     | 230.4643   | 7.7059      | 0.045    | 3.36                 | 1.41        | 0.98        | 600.3            | 0.63 | 0.0048         | 0.0172         | 86        | 27        |
| MKW8   | 15    | 220.1596   | 3.4177      | 0.027    | 2.31                 | 1.24        | 0.82        | 529.4            | 0.50 | 0.0026         | ...             | ...       | 94        |

High-mass clusters

Low-mass clusters

Note. Column (1): Name. Column (2): number of galaxies included in our main sample. Columns (3)–(7): R.A., decl., z, M_200 and R_200 of the cluster centers; high-mass cluster values are taken from Reiprich & Böhringer (2002), and low-mass cluster values from Xu et al. (2018). Columns (8), (10), and (13): R_500 and (double-)beta model parameters (β, r_e, r_e2); high-mass cluster values are taken from Eckert et al. (2011), and low-mass values from Xu et al. (2018). When only a single-beta model is available, the parameters for the second beta component are written as—. Column (9): velocity dispersion of the clusters, estimated from M_200 (see Section 2.1.1). Columns (11) and (12): central density of ICM for (double-)beta models, estimated from M_{gas,500} and the (double-)beta models (see Section 3.1); ρ_{g} = 1.4NH/m_p, where m_p is the mass of proton.

derived in different ways for the high-mass and low-mass clusters.

Because nearly one third of the X-ray luminous, high-mass clusters have cool cores, deviating from the hydrostatic equilibrium and isothermal state, Eckert et al. (2011) use a scaling relation to estimate R_200 from the virial temperature of the clusters (Hudson et al. 2010). The median ratio of R_200 from Reiprich & Böhringer (2002) over R_200 from Eckert et al. (2011) is 1.44 ± 0.08, which is comparable to R_{500}/R_{200} = 1.50 expected from an NFW profile, assuming a halo mass of 3 × 10^{14} M_☉ and a concentration of 4. Eckert et al. (2011) combined XMM-Newton and Chandra data to derive the X-ray surface brightness profiles for the high-mass clusters. Because a single-beta model does not describe the shape of the radial profile in cool-core clusters well, Eckert et al. (2011) fit a double-beta model for cool-core clusters and a single-beta model for no-cool-core clusters. We use the (double-) beta models from Eckert et al. (2011) to derive ICM densities.

Following Xu et al. (2018), we assume a single-beta model for the low-mass clusters, fixing β = 2/3 and r_e = R_{500}/7, where R_{500} has been obtained from the curve-of-growth fitting.

We then estimate M_{gas} and ρ(0) in a similar way as for high-mass clusters.

We approximate the ram pressure as P = ρ(d_{proj}) Δv_{rad}^2. This approximation has a few uncertainties, including

1. Projection effects. ρ(d_{proj}) can only be viewed as an upper limit of ρ(d). Similarly, Δv_{rad} can only be viewed as a lower limit of Δv. Despite these obvious offsets, we find that ram pressure estimated in this way still leads to useful analysis. We will further discuss the influence of the projection effects on our main results in Section 5.

2. Extrapolation effects. The ROSAT data typically does not detect ICM out to 2R_{200}. For high-mass clusters, the typical maximum radius to detect X-ray flux in a cluster is ~0.92R_{200} (Reiprich & Böhringer 2002), and for low-mass clusters, it is ~0.63R_{500} (Xu in prep.). So when d_{proj} is larger than the maximum detectable radius, ρ(d_{proj}) has uncertainties due to extrapolation.

3. Sub-structures in the ρ distribution. These structures are typically associated with infalling groups or galactic mergers, which induce shocks in the ICM (Markevitch & Vikhlinin 2007; Tonnesen & Bryan 2008; Roediger et al. 2014; Ruggiero et al. 2019), and sometimes significantly
raise the local level of ram pressure (Kenney et al. 2004). This type of shock was found in some of our selected clusters (e.g., A 1367, Ge et al. 2019). Because most of the cluster merger associated shocks found so far are distant (>1 Mpc) from the cluster center and weak (with Mach number <3, Markevitch et al. 2005; Markevitch & Vikhlinin 2007; Ogliari et al. 2014; Dasadia et al. 2016; Itahan et al. 2015), we assume that the filling factor of strong shock fronts to be small in a typical cluster at low redshift, and do not significantly affect statistical analysis.

4. Isothermal assumption. Because the temperature drops in the core region of high-mass, cool-core clusters, ρ in the same region are likely under-estimated. However, because the temperature variations are typically less than twice in the core region of clusters in the high-mass cluster sample (Hudson et al. 2010), and the X-ray power emissivity scales with $T^{2}$ (so for the same X-ray surface density, $\rho \sim T^{-0.25}$), the under-estimation of $\rho$ should be small (<0.1 dex).

3.2. HI Density Profile and Anchor Force

The anchor force to hold the interstellar medium gas at a radius $r$ in the galactic disk plane can be calculated as

$$F_r = 2 \pi G (\Sigma_{*r} + \Sigma_{H I r}) \Sigma_{H I} r,$$

where $\Sigma_{*r}$ and $\Sigma_{H I r}$ are the stellar and HI surface density (multiplied with a factor of 1.36 to account for helium) at $r$. This is a modified form of the Gunn et al. (1972) formalism, to take into account the self-gravity of the HI gas, which cannot be ignored in the outer disks. Similar modifications can be found in Stevens & Brown (2017), Fujita (2004), Abadi et al. (1999).

We estimate the anchor forces $F_{R25}$ and $F_{RHI}$ at two characteristic radii, $R_{25}$ and $R_{HI}$. We use the method outlined in Wang et al. (2020) to estimate $\Sigma_{HI R25}$ for each galaxy. The method makes use of the HI size-mass relation, and the homogeneous shape of HI radial profiles in the galactic outer region. This method works best when the given radius is within the exponential dropping part of the HI surface density profile, and $R_{25}$ is a good option of such radius. Following the previous work of Jaffé et al. (2018) and others, we assume an exponential disk for the stars, so that the central stellar surface density $\Sigma_{*0} = M_*/2\pi R_d^2$, and $\Sigma_{*r} = \Sigma_{*0} e^{-r/R_d}$, where $R_d$ is the r-band scale-length.

There are also a few uncertainties related to these estimates.

1. Assumption of universal HI radial profiles in the outer disks. Galaxies in clusters may have perturbed HI profiles. Luckily, Wang et al. (2016) found that galaxies from the VIVA (VLA Imaging of Virgo Spirals in Atomic Gas, Chung et al. 2009) survey lie on the same HI size-mass relation as other galaxies. We further test our method of estimating $\Sigma_{HI R25}$ with the VIVA data. When galaxies are selected in the same $M_*$ and $R_{HI}/R_{25}$ range as our main sample (in total 16 galaxies), the median offset between the predicted and observed values of $\Sigma_{HI R25}$ is 0.08 ± 0.16 dex (see Appendix B). In comparison, the distribution of $\Sigma_{HI R25}$ has a scatter of 0.31 dex, so the prediction indeed helps constrain the value.

2. Only disk stars and HI gas are considered in the gravitational potential. We ignored gravity from the bulge stars, molecular gas and dark matter. Because we consider the anchor forces in a relatively distant outer region, the gravity from a central spheroidal bulge is usually small (Abadi et al. 1999). The molecular disks usually do not extend beyond $R_{25}$ and should contribute little to the disk gravity. The contribution of the dark matter to the gravity that holds gas in the disk mid-plane should be negligible due to the low volume density, which was confirmed in Jaffé et al. (2018).

3. Over-estimates of the disk masses. By ignoring the bulge, we may over-estimate $\Sigma_{*,0}$, and therefore over-estimate the anchor force. We use the linear equation of Catinella et al. (2013), which was based on the galactic decomposition catalog of Gadotti (2009), to roughly convert the concentration index $R_{de}/R_{50}$ to the bulge-to-total mass ratio $B/T$. We test by using the derived $1 - B/T$ to scale down $\Sigma_{*,r}$ and recalculating the anchor forces. We do not find the results presented later in Section 4 to significantly change after this treatment. This happens because by selection our galaxies are disk-dominated, with $R_{de}/R_{50}$ having 10, 50 and 90 percentiles of 1.97, 2.31 and 2.73, corresponding to estimated $B/T$ of 2%, 17% and 36%. However, we note that estimating $B/T$ in this way is crude, particularly because our galaxies extend to much lower $M_*$ than the limit (>$10^{10} M_\odot$) of Gadotti (2009).

4. We ignored the protection/pressure from the circumgalactic hot gas halo, which needs to be stripped before the HI gas directly feels the ram pressure. Because previous studies suggested that strangulation of galaxies due to halo gas removal starts at $5R_{200}$ from the cluster center (Bahé et al. 2013), the problem of ignoring pressure from the halo gas is mitigated.

3.3. The Strong, Weak, and No-RPS Galaxies

We can view the ratio between the ram pressure and the anchor force as a measure of RPS strength. We divided our sample of galaxies into three types with the following criteria:

1. Strong-RPS: $P > F_{R25}$, including 17 (13%) and 3 (3%) galaxies in high-mass and low-mass clusters, respectively.

2. Weak-RPS: $F_{RHI} < P < F_{R25}$, including 70 (52%) and 33 (30%) galaxies in high-mass and low-mass clusters, respectively.

3. No-RPS: $P < F_{RHI}$, including 48 (35%) and 73 (67%) galaxies in high-mass and low-mass clusters, respectively.

Atlases of SDSS images and ALFALFA HI spectrum of the 20 strong-RPS galaxies can be found in Sections A.1 and A.2 in the Appendix.

By definition we expect that on average the strong-RPS galaxies are strongly stripped by ram pressure near or on the stellar disks, the weak-RPS galaxies just start to feel the ram pressure in the very outer region of their HI disks, and no-RPS galaxies are not strongly affected by ram pressure in either the HI or stellar disks.

Because both ram pressure and anchor force have uncertainties in the estimates, the division into these three groups should be viewed as being statistically representative instead of being absolutely accurate. We also remind that all the galaxies in the main sample are ALFALFA detected, HI-rich galaxies, and do not represent the general galaxy population. The sample should
also have significantly missed the galaxies that suffer from strong RPS and become highly deficient in HI. The galaxies in this sample are thus selected to search for candidates under relatively weak RPS on the HI and at a relatively early stage of being processed by the environment when they are moving through the clusters.

4. Results

4.1. Projected PSD Positions Versus Internal Surface Densities and the Determination of RPS Strength

Previous studies have demonstrated that the projected PSD is not only reliable for identifying cluster members but also useful to statistically assign cluster members to different infall stages (Oman et al. 2013). Virialized galaxies tend to lie in a triangular region around the cluster center in the projected PSD, while galaxies that are infalling for the first time tend to have higher $\Delta v$ at a given $d_{\text{proj}}$. For convenience, we call them virialized and infalling galaxies respectively. We keep in mind that galaxies may transport between the pericenter and apocenter (the “backsplash” galaxies) several times before finally virialized. According to the literature, nearly half of the galaxies at small $D_{\text{vir}}$ (e.g., $< \sigma_C$) and slightly beyond the virialized region ($1-2R_{200}$) can be backsplash objects (Mahajan et al. 2011; Jaffé et al. 2015).

In the bottom row of Figure 2, the different RPS types separate well on the projected PSD. We further divide them into infalling and virialized types, and summarize their numbers in Table 2. In Table 2, the strong-RPS galaxies are not divided according to their infall status because they are found continuously across the projected PSD. Most of the strong-RPS galaxies are found in the high-mass clusters, and in the infalling region. They dominate the HI-rich galaxy population of high-mass clusters when $d_{\text{proj}} < 0.5R_{200}$. The weak-RPS galaxies are also found mainly in the infall region, but extend further in high-mass clusters than in low-mass clusters. They are rarely found beyond $d_{\text{proj}}/R_{200} \sim 1.2$ in low-mass clusters, but are common ($\sim 40\%$ among the three RPS types, top row of Figure 2) at $d_{\text{proj}}/R_{200} \sim 2$ in high-mass clusters. The no-RPS galaxies concentrate in the “backsplash”...
region \(d_{\text{proj}} > R_{200}\) and \(\Delta v_{\text{rad}}/\sigma_c < 1\) in high-mass clusters. They are dominantly found in two regions of the low-mass clusters: the outskirts where \(d_{\text{proj}} > 1.2R_{200}\), and the virialized region where \(d_{\text{proj}} > 0.5R_{200}\).

In the other panels of Figure 2, we can see that the strong-RPS galaxies tend to have low \(\Sigma_{\text{HI},R25}\) and low \(\Sigma_{\text{HI},R25}\), hence low anchor forces at \(R_{25}\). The weak and no-RPS galaxies are less different from each other in these properties.

In summary, the RPS strength strongly depends on the cluster mass and the projected PSD position. Such strong dependence on PSD positions was noticed before (Jaffé et al. 2018; Yun et al. 2019). Although the RPS strength is determined by both the ram pressure and the anchor force, the former (reflecting the external environments) seems to play a dominant role in regulating the evolution of HI-rich galaxies.

The regulating role of anchor forces (reflecting the internal properties) rises only when the RPS is strong, probably after an earlier stage of weak RPS, which has reduced \(\Sigma_{\text{HI},R25}\) and thus the anchor forces.

4.2. HI Mass and Central SFR Compared to Control Galaxies

As the reservoir of material for star formation, the HI richness is strongly correlated with the star-forming status of field galaxies and determines the future potential of forming stars. A lower \(M_{\text{HI}}\) than control galaxies that have similar integral SFR would be the signature of recent, violent removal of the HI gas, and predictable of a drop in SFR in the near future.

Past studies (Kauffmann et al. 2003; Li et al. 2015) showed that some spectral indices are good tracers of the recent star-forming activities. Higher specific SFRs are typically associated with lower \(D_{\text{4000}}\) and higher \(\text{EW}(\text{H} \alpha)\). We remind that the control galaxies are matched in the global SFR to the main sample, and the SDSS spectral indices are measured for the galactic central regions. So if the main sample galaxies have lower central \(D_{\text{4000}}\) and higher central \(\text{EW}(\text{H} \alpha)\) than the control galaxies, it can be interpreted that these galaxies have higher central SFR but lower SFR in the outer regions when compared to the control galaxies. Such an outside-in star formation cessation is often linked to gas stripping (Koopmann & Kenney 2004a, 2004b; Boselli et al. 2006; Fabello et al. 2012; Fossati et al. 2013). Meanwhile, if strong central starbursts happened in the past 10 Myr, then galaxies are expected to have higher central \(\text{EW}(\text{H} \alpha)\) for their central \(D_{\text{4000}}\) (Li et al. 2015).

We compare the \(M_{\text{HI}}\) and central SFR of main and control samples in Figures 3 and 5. We focus on the extent of differences each of the RPS subsamples (strong, weak and no) shows with respect to their control galaxies. However, we will refrain from interpreting the apparent differences between the three subsamples because \(M_{\text{HI}}\) and SFR depends on several additional parameters (e.g., \(M_\star\), disk-bulge structure), which are not matched between the subsamples.

Strong-RPS galaxies are shown in the third row of Figure 3, which are mostly observed in the high-mass clusters. They tend to have on average higher central \(\text{EW}(\text{H} \alpha)\) but similar central \(D_{\text{4000}}\), indicative of enhanced central starbursts compared to their control galaxies. They also have lower \(M_{\text{HI}}\) than the control galaxies.

Three strong-RPS galaxies in the high-mass clusters have been excluded from this analysis because not enough control galaxies could be found (atlas in Figure 10 in the appendix). Two of these galaxies have significantly higher SFR than all other galaxies with similar \(z\), \(M_\star\) and \(\mu_\star\) in the control galaxy pool. The abnormalities in SFR are consistent with the enhanced central \(\text{H} \alpha\) emission in the strong-RPS galaxies that have control galaxies. The remaining galaxy without a control galaxy is an elliptical galaxy from the SDSS image. It has low integral SFR \(\sim 10^{-1.15} M_\odot \text{yr}^{-1}\), but significant \(M_{\text{HI}} \sim 10^{9.3} M_\odot\), which is 0.46 dex higher than expected for its \(M_\star \sim 10^{10.4} M_\odot\) and SFR (Saintonge et al. 2016). Like in other HI-rich early-type galaxies, its HI may have been obtained through mergers and maintained in the form of an extended disk, which does not easily flow to the galaxy center to fuel the star formation there (Serra et al. 2012).

The weak-RPS galaxies in the high-mass clusters have on average slightly higher central \(\text{EW}(\text{H} \alpha)\) than the control samples (second row of Figure 3). We find similar results when only selecting the infalling galaxies (second row of Figure 4), but do not have a large enough sample to conclude anything about the virialized weak-RPS galaxies. Similar results are found in the low-mass clusters (second row of Figure 5, and second row of Figure 6). None of the weak-RPS subsets show significantly different \(M_{\text{HI}}\) distribution compared to the control galaxies.

The no-RPS galaxies do not significantly differ from their control galaxies in the distributions of central \(\text{EW}(\text{H} \alpha)\), central \(D_{\text{4000}}\), or \(M_{\text{HI}}\). This result holds when selecting either virialized or infalling galaxies, and in both low-mass and high-mass clusters (Figures 5, 3 and 6).

5. Discussion

Combining HI data of galaxies with extended X-ray data of clusters has previously been conducted for individual clusters
but this paper for the first time works on a relatively complete overlap between the largest HI blind survey ALFALFA and the largest X-ray blind survey ROSAT. The galaxies were selected from two complete catalogs of clusters with extended X-ray emissions. In particular, the RXGCC sample is lately built with a novel algorithm to search for faint clusters from the whole ROSAT dataset. The extended X-ray fluxes ensure $M_{200}$, $R_{200}$ and $n_{ICM}$ to be derived in relatively accurate ways. The results presented in this study can thus be compared to simulations in a relatively convenient way in the future by producing mock catalogs with similar survey parameters as ALFALFA and ROSAT.

We point out that the major goal of this study is neither characterizing galactic features under RPS nor providing a census of galaxies under strong RPS because the sample is strongly biased against HI-deficient galaxies. Instead, as a test of our classification method (Section 5.2) we examine whether the observed HI and SFR properties are consistent with expectations when galaxies are under RPS. We then discuss the role that weak RPS might play in cluster galaxy evolution, based on the PSD distribution and frequency of weak-RPS galaxies in our sample (Section 5.3).

5.1. Past Studies on HI and SFR Properties of Galaxies in the Coma and A1367 Clusters

We note that a considerable fraction of the main sample galaxies come from the Coma and A1367 clusters. The HI and SFR properties of galaxies in these two clusters have previously been extensively studied.

Studies based on wide-field, blind HI surveys found that the distribution of HI-detected galaxies is much less concentrated on the cluster centers than optically detected galaxies (Cortese et al. 2008) and galaxies are more HI-deficient when the local densities are higher (Gavazzi et al. 2013). Studies based on ultraviolet, infrared and Hα images consistently found the outside-in suppression of SFR at high local densities (Gavazzi et al. 2013; Cybulski et al. 2014). These statistical results support a picture where ram pressure plays an effective role in removing HI from galaxies.

Interferometric HI images further confirmed the on-going RPS for a number of galaxies. The HI disks of observed galaxies in the Coma and A1367 clusters often display lopsided morphologies, which are displaced center from the optical counterparts, and/or smaller extension than the optical disks (Bravo-Alfaro et al. 2000, 2001; Scott et al. 2010, 2018). The ubiquitous RPS in the Coma cluster was also confirmed from
observing the warm ionized gas with deep H\textalpha images (Yagi et al. 2010, 2017; Gavazzi et al. 2018).

5.2. Relating the Observed Trends in this Study to RPS

We find that only the strong-RPS galaxies show evidence for a significant reduction in $M_{\text{HI}}$ compared to the control galaxies. strong- and weak-RPS galaxies show higher central $EW(H\alpha)$ in the galactic center than the control galaxies, and the no-RPS galaxies are no different from the control galaxies in either $M_{\text{HI}}$ or the central $EW(H\alpha)$. We discuss possible physical mechanisms relating RPS to these observed differences.

5.2.1. Differences in $M_{\text{HI}}$

The strong-RPS galaxies have on average lower $M_{\text{HI}}$ than the control galaxies, which suggests a fast removal of H\texti. However, H\texti does not directly form stars but fuels star formation as part of the circle of gas accretion, gas inflow, star formation and outflow (Krumholz et al. 2018; Wang et al. 2020). So at a given $M_{\text{HI}}$, SFR is adjusted to the available H\texti on a timescale longer than the freefall time of molecular gas (Krumholz et al. 2012) but shorter than the H\texti depleting time (Saintonge et al. 2017). Under strong RPS, the gas removal can be much quicker than the capability for SFR to be adjusted to $M_{\text{HI}}$. For extreme cases of galaxies in the stripping region of the projected PSD, gas removal has a timescale of a few $10^7$ yr (Abadi et al. 1999). Our result is consistent with previous findings that the detection rate and mass fraction of H\texti drops much more quickly than the specific SFR near the cluster centers (Fabello et al. 2012; Jaffé et al. 2015). By cross-matching with nearby galaxies that are known to display RPS gas tails, we can confirm that at least 4 out of the 17 strong-RPS galaxies are indeed among those with tails (see Section A.3 of Appendix). This confirmation rate should be viewed as a lower limit because not all of our clusters have been searched for RPS features in the morphology. Gas removal in low- and no-RPS galaxies seems to be much slower.

One direct reason for this is that a smaller radial range of H\texti is affected in low-RPS galaxies than in high-RPS galaxies. Additionally, there is a time lag between gas being stripped off the disk plane and reaching the escape velocity of the galaxy, which is longer when the ram pressure is weaker (Roediger & Brüggen 2007). In addition to RPS, tidal stripping or harassment may also contribute to reducing $M_{\text{HI}}$ in the weak- and no-RPS galaxies because their velocities are lower than those of the strong-RPS galaxies. Nevertheless, the combined efficiency of removing H\texti is not as high as in the strong-RPS galaxies.

5.2.2. Differences in the Central SFR

The strong-RPS and low-RPS galaxies show higher central $EW(H\alpha)$ in the center when compared to their control galaxies, consistent with the consequence of RPS. Higher values of central $EW(H\alpha)$ compared to the control sample could indicate either recently enhanced central SFRs or suppressed SFRs in the outer disks. If the strong-RPS or low-RPS galaxies had on average lower central $D_{4000}$ values than their control galaxies, then it would be strong evidence for suppressed SFR in the outer region. However, we observed no significant difference in central $D_{4000}$ between the low-RPS (strong-RPS) galaxies and their control galaxies. Considering the fact that $D_{4000}$ may not be as sensitive as $EW(H\alpha)$ to small changes in the SFR, we discuss both possibilities regarding whether SFR is suppressed in the outer disks.

If the SFR is indeed suppressed in the outer region of strong- and low-RPS galaxies, then it strongly supports a scenario of outside-in quenching as a result of outside-in gas stripping. Such a stripping scenario is consistent with the nature of RPS because the anchor force is weaker at larger galactic radius. RPS could then perfectly explain the central $EW(H\alpha)$ enhancements in strong- and weak-RPS galaxies compared to no-RPS galaxies.

It is also plausible that the strong- and weak-RPS galaxies have enhanced central SFR instead of (or in addition to) suppressed outer SFR. Theoretical studies predicted the enhancement of SFR when pressure from the ICM or shocks at the ICM-disk interface compress the cold gas, before the gas is severely stripped (Steinhauser et al. 2016; Safarzadeh & Scannapieco 2017; Ramos-Martínez et al. 2018). In several simulations, the process is accompanied by significant gas inflows and is generated directly by oblique shocks (Ramos-Martínez et al. 2018) or loss of angular momentum in interaction with the ICM (Tonnesen & Bryan 2009), which results in enhanced central SFR (Kronberger et al. 2008; Tonnesen & Bryan 2012; Bekki 2014). Observational studies also found enhanced SFR prevalent in galaxies undergoing ram pressure (Jaffé et al. 2016; Vulcani et al. 2018; Roberts & Parker 2020). However, the preferred location within galaxies for SFR to be enhanced is still a question of debate, and can be located in the ICM-disk interface (Ebeling et al. 2014; Lee et al. 2017; Ramatsoku et al. 2019), in the center (Mok et al. 2017), or at the all galactic radius (Vulcani et al. 2020). The enhanced central SFR in strong-RPS galaxies is thus not against the findings in the literature.

The mechanism of enhancing central SFR might be more complex in the weak-RPS galaxies. Since the low-RPS galaxies tend to be in the relatively outer region of the cluster, tidal interactions with both the cluster (Byrd & Valtonen 1990) and surrounding galaxies (Mihos et al. 1992) might also play a role by driving gas inflows. However, interestingly, in low-mass clusters, the virialized, no-RPS galaxies do not show enhanced central SFR, although they are in a similar $\delta_{\text{proj}}$ range and thus similar cluster gravities and local densities as the infalling, low-RPS galaxies. These virialized, no-RPS galaxies should even suffer from more effective tidal interaction with the surrounding galaxies, due to their lower velocities than the infalling, low-RPS galaxies. However, they do not show as much enhanced central SFR as the infalling, low-RPS galaxies. It is possible that galactic tidal effects even in the outer region of these massive clusters are generally weak (Boselli et al. 2006), and take the form of harassment (Moore et al. 1996, 1998) instead of interactions, which heat the disks but do not efficiently drive gas inflows. Meanwhile, tidal interaction with the cluster may not be so efficient at these relatively large distances, and indeed we find that all of the infalling, low-RPS galaxies have a cluster perturbation strength ($M_{200}/M_\text{clus}((\pi/4)^4(R_{200}/d_{\text{proj}}))^3$ that is lower than the critical value of 0.15 for triggering nuclear activities (Byrd & Valtonen 1990). It implies that ram pressure

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5 This critical value of 0.1 assumes that the galaxy preserves its dark matter halo (Byrd & Valtonen 1990), which is reasonable because 90% of the infalling, weak-RPS galaxies have tidal radius $r_{\text{tid}} \sim 0.5$ $d_{\text{proj}}$, $W_{\text{ICM}}/c > \sim 0.25$ (Merritt 1984) in both low and high-mass clusters. The tidal radius has been defined as the galactic radius beyond which material is effectively removed by tidal effects. For reference, if we assume that no dark matter remains, then the critical value of cluster tidal perturbation strength drops to 0.006 (Byrd & Valtonen 1990), and 70% (38%) of infalling, weak-RPS galaxies in high-mass (low-mass) clusters are perturbed according to this criteria.
may be the mechanism that enhanced the central SFR in the weak-RPS galaxies.

5.2.3. Feasibility of the RPS Strength Parameter

As discussed earlier, cluster galaxies under stronger RPS exhibit more significant difference in \( M_{\text{HI}} \) and central SFR from their control galaxies. It is worth noting that the three RPS types occupy different regions of the projected PSD in high-mass and low-mass clusters. This difference is expected because \( \sigma_C \) of the high-mass clusters is higher, leading to higher \( \Delta v_{\text{rad}} \) at a given projected PSD position than in the low-mass clusters. But, the low-mass and high-mass clusters show consistent results when comparing the different RPS types to control galaxies. This implies that the RPS strength parameter has captured a fundamental property of the environmental processing. Although the RPS strength parameter combined several observables of external and internal properties, the way in which these observables are combined is not arbitrary but is motivated by the RPS theory. Although the way of inputting the observables to the calculation of PRS strength has uncertainties, it seems that the physical effect of RPS is strong enough in the massive clusters to override many of the uncertainties.

Thus, we conclude that our classification of galaxies into the three RPS types is statistically successful.

The way that we define the three populations can be effectively used to combine galaxies from different clusters. In statistical analysis, cluster galaxies were often binned into subsample by more directly observed parameters, such as \( d_{\text{proj}}/r_{200} \), here we have introduced \( P/F_{\text{R25}} \) as a new parameter to bin subsamples. This new parameter can be conveniently derived in cosmological simulations, and helps separate RPS from other processes/parameters that influence galaxy evolution.

5.3. Radial Extension of RPS in the Massive Clusters

Early statistical studies on environmental effects in groups/clusters focused on the cluster-centric trend of galaxy properties (or similarly, galaxy properties as a function of local densities). These studies found that galaxies on average become more H\textsc{i}-deficient and passive toward the cluster center (Gavazzi et al. 2006; Weinmann et al. 2006; Gavazzi et al. 2010; von der Linden et al. 2010; Yoon & Rosenberg 2015; Odekon et al. 2016; Brown et al. 2017), implying accelerated galaxy evolution in clusters. This trend is found to be steeper in high-mass clusters than in low-mass clusters (Hess & Wilcots 2013; Woo et al. 2013; Yoon & Rosenberg 2015; Brown et al. 2017), more significant for low-mass galaxies than for high-mass galaxies (Wetzel et al. 2013; Woo et al. 2013; Zhang et al. 2013; Woo et al. 2017), consistent with the way that RPS is predicted to work. Later, it was found that galaxy properties also vary as function of radial velocity offsets from the cluster center at a given projected distance (Pimbblet et al. 2006; Mahajan et al. 2011; Barsanti et al. 2016; Bayliss et al. 2017; Nascimento et al. 2019). With the aid of cosmological simulations, it becomes clear that positions on the PSD are associated with galaxies at different infall stages, which thus show a correlation with the averaged galactic properties (Gill et al. 2005; Boselli et al. 2014b; Haines et al. 2015).

The PSD is an excellent tool to study RPS, not only because it can identify infalling galaxies that may have more gas to be stripped (Oman et al. 2013; Haines et al. 2015; Rhee et al. 2017) but also because its two axes almost fully determine the ram pressure for a given cluster (Gunn et al. 1972). Only the projected PSD is available in observations, but has been proven to be statistically powerful in linking infall stages, stripping events, gas-richness and star-forming status of galaxies (Boselli et al. 2014b; Muzzin et al. 2014; Oman & Hudson 2016; Yoon et al. 2017).

The pioneer studies utilizing the projected PSD to study RPS of \( \text{H} \text{i} \) in galaxies found remarkable consistency between observed and predicted \( \text{H} \text{i} \) richness. These studies typically assume exponentially radial distributions for both the HI and stars, and the scale-length of an HI disk is set to be a fixed factor of that of the stellar disk. Then, based on the equation of Gunn et al. (1972) and setting the relative velocity to be \( \sigma_C \), a limiting “stripping region” can be defined in the projected PSD where the ram pressure becomes stronger than the anchor force at all galactic centric radii; and thus the gas in galaxies is expected to be significantly removed within this region. The detection rates of galaxies in blind HI surveys abruptly drop, and the fractions of red galaxies significantly increase after passing that limit (Jaffé et al. 2015, 2016; Yoon et al. 2017; Jaffé et al. 2018). These results lend strong support to RPS driving galaxy evolution in massive clusters, in a more direct way than previously using cluster-centric radial trends.

Our work is built upon these previous analyses with two new components added to the method. The first new component is that we use a more realistic radial distribution of \( \text{HI} \) when estimating the anchor forces. Compared to the exponential model that is often assumed in the previous studies, a real HI disk tends to have a flattened surface density distribution, and sometimes has a central hole in the inner region. Thus, for the same \( M_{\text{HI}} \) and scale-length, a real disk tends to have more mass and hence higher surface densities in the outer region, resulting in higher anchor forces. Additionally, statistical analysis based on HI images found that the HI scale-length \( \sim 0.2 R_{\text{HI}} \) (Wang et al. 2014, 2020), which strongly depends on \( M_{\text{HI}} \) but not on the optical scale-length. The ratio between the HI and \( r \)-band scale-lengths of our main sample galaxies ranges from 0.7–1.9 in both high-mass and low-mass clusters. Therefore, assuming a fixed ratio of the scale-lengths as used in the previous studies will introduce additional uncertainties in HI surface densities at a given galactic radius. The second new component of the method is that we focus on an earlier phase of stripping, when ram pressure is just enough to strip the HI at \( R_{\text{peri}} \) and \( R_{\text{HI}} \). The selection of galaxies with \( R_{\text{HI}} > R_{\text{peri}} \) also ensures that most galaxies have not yet entered the classical “stripping region.”

We thus included the self-gravity of HI when calculating the anchor forces, which is usually ignored when discussing stripping of the inner disks where stars dominate the gravity. We also used \( \Delta v_{\text{rad}} \) instead of \( \sigma_C \) when calculating the ram pressure, to better reflect the fact that during infall galaxies are accelerated while approaching the pericenter. A few interesting features show up with this new scheme of classifying galaxies into strong-, weak- and no-RPS populations. We summarize the scenario in Figure 7 and discuss a few key points below.

First, strong-, weak- and no-RPS galaxies overlap significantly in \( d_{\text{proj}} \). Thus, the scatter in the previously quantified cluster-centric radial trends of gas richness (Hess & Wilcots 2013; Odekon et al. 2016; Brown et al. 2017) can be explained at least partly by this feature. As already mentioned, at a given \( M_{200} \), the projected PSD position traces the ram pressure of different levels much more closely than \( d_{\text{proj}} \). The higher
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Figure 7. Toy scheme of an HI-rich galaxy passing different RPS regions while traveling through a massive cluster. Like in Figure 2, the black-dashed curves mark the escape velocity and the virialized region. The arrowed blue curve is the trajectory of the galaxy starting from $d_{\text{proj}} \sim 2R_{\text{200}}$, shrinking due to dynamic friction until getting virialized. The purple, green and red regions are divided by curves of equivalent ram pressure, and approximately correspond to the no, weak and strong-RPS regions, because RPS strengths are largely determined by the relative velocity of the galaxy and the density of the ICM. But the gradually reduced anchor force due to the galaxy starting from the cluster-centric distance of $R_{\text{200}}$ and $R_{\text{200}}$ can account for one third of the total gas loss in a galaxy during the infall process between $R_{\text{200}}$ and the pericenter (Steinhauer et al. 2016, their Figures 2 and 4). At this point, we are still unable to directly compare in observations the relative importance of RPS to tidal stripping of the cluster and other environmental effects (harassment, viscosity stripping, thermal evaporation, etc.), but we showed that for a significant fraction of gas-rich galaxies at and beyond $R_{\text{200}}$ of massive clusters, ram pressure is likely already causing HI loss. The high incidence of RPS in HI-rich galaxies at $R_{\text{200}}$ is consistent with the prediction of the simulation IllustrisTNG-100 (Yun et al. 2019). Environmental processing beyond $R_{\text{200}}$ is commonly termed pre-processing and attributed to effects in groups (Bahé et al. 2013; Bahé & McCarthy 2015; Bahé et al. 2019), but our results suggest that part of the “pre-processing” around the most massive clusters could actually be processed by the cluster itself through weak RPS.

5.4. Uncertainties and Future Perspective

We warn readers again about the uncertainties related to the estimates of the RPS parameter. Among those discussed in the paper, the most obvious is the projection effect. Luckily, because massive clusters strongly concentrate galaxies, a $d_{\text{proj}}$ is associated with a relatively narrow distribution $d$ with the median value slightly larger than but close to $d_{\text{proj}}$ (in contrast, in the field $d_{\text{proj}}$ and $d$ are much more different). Similarly, $\Delta v_{\text{rad}}$ is much closer to $\Delta v$ than they would be in looser environment. We roughly quantify the difference between $d_{\text{proj}}$ and $d$ by selecting...
all the 280 clusters with \( M_{200} \geq 10^{14} \, M_\odot \) (having in total 23295 galaxies with mass \( > 10^9 \, M_\odot \)) from the TNG300 run in the suite of IllustrisTNG cosmological simulations (Springel et al. 2018; Nelson et al. 2019). From Figure 8, we can see that at all \( d_{\text{proj}} \), the majority (>80%) of the cluster galaxies have \( d \) differ by less than 40% from \( d_{\text{proj}} \) (see also Mahajan et al. 2011). This is an important reason why with projected distances, the estimated ram pressure still statistically select galaxies with SFR and HI properties consistent with the expected RPS. We roughly assess the uncertainty of approximating \( d \) with \( d_{\text{proj}} \), by replacing \( d_{\text{proj}} \) with \( 1.5d_{\text{proj}} \) when estimating \( \rho \). Then, \(~45\%\) of the main sample galaxies are under weak RPS at \( 1.6R_{200} \) in the high-mass clusters; only 25% of the main sample galaxies, but nearly half of the infalling subset are under weak RPS at \( R_{200} \) in the low-mass clusters. Because \( \Delta v_{\text{rad}} \) is an under-estimate of \( \Delta v \), the real ram pressure is likely to be stronger and more galaxies may be under weak RPS at these distances than classified with \( \Delta v_{\text{rad}} \). So our main result that weak-RPS affects a significant fraction of galaxies near and beyond \( R_{200} \) is likely to be robust. We emphasize that application of the method should always be limited to statistical analysis, and future comparison with hydrodynamic and semi-analytical simulations may help us quantify and correct for the limitations. Most previous comparisons between the observation and the simulation were in the form of comparing scaling relations and cluster-centric radial distribution of observable parameters, which reflect the result of complex physical processes mixed together. Our RPS strength parameter provides an opportunity to (at least partly) separate RPS from other environmental and internal processes in such comparisons. For example, recent \( \Lambda \)CDM SAMs have found that RPS of cold gas is a necessary component in the model to reproduce the observed level of HI mass fractions in relatively high-mass satellite galaxies, but the HI mass fraction of low-mass satellite galaxies, and the offsets of HI related scaling relations between central and satellite galaxies are difficult to reconcile (Gonzalez-Perez et al. 2014; Henriques et al. 2015; Luo et al. 2016; Stevens & Brown 2017; Cora et al. 2018). Directly comparing to the observed distribution of RPS strength and to the observed HI property as a function of RPS strength may help us to identify whether and which part of the RPS recipe in SAMs needs to be improved.

![Figure 8](image.png)

Figure 8. Violin plot of the difference between \( d \) and \( d_{\text{proj}} \) of galaxies in clusters selected from the TNG300 run in the IllustrisTNG project. Only galaxies with mass \( > 10^9 \, M_\odot \) are selected. The three bars of each violin represent the 10, 50 and 90 percentiles of the distribution. The distributions do not change much if we only select infalling galaxies, or exclude the backsplash galaxies.

The sample used in this study is still relatively small, thus the differences between strong/weak-RPS and control galaxies are marginal in each individual panel of Figures 3–6. The differences remain consistent in all these figures, which adds strength to their statistical significance, but they need confirmation with larger samples in the future.

Finally, as in many other studies utilizing ALFALFA data (e.g., Odekon et al. 2016), we are limited by the depth of HI data, which biased the sample against low-mass galaxies. We look forward to deeper and more HI detections with the upcoming CRAFTS (Zhang et al. 2019), Apertif (Verheijen et al. 2009), and WALLABY (Koribalski et al. 2020) surveys. HI images are commonly used to search for RPS tails. However, because the observability of tails depends on the angle of the line of sight from the direction of infall and on the image resolution, our method can be used to select RPS candidates that do not show obvious tails. This application is particularly useful given that the majority (90%) of galaxies that will be detected in these new HI surveys will not be well resolved (Staveley-Smith & Oosterloo 2015).

### 6. Summary and Conclusion

So far as we know, this is the first statistical study on ALFALFA detected galaxies in more than 10 clusters with well-parameterized extended X-ray emissions (i.e., with resolved X-ray surface brightness radial profiles). The sample of clusters extends to \( M_{200} \sim 4 \times 10^{13} \, M_\odot \), thanks to the new RXGcC catalog (Xu et al. 2018, Xu et al. in prep), which is built with the state-of-art algorithms to search for faint and extend X-ray sources. We described a promising method to parameterize the RPS strength in clusters, based on the theory of Gunn et al. (1972) and improved upon the previous observational achievements. We compared the \( M_{\text{HI}} \) and central SFR of over 200 HI-rich cluster galaxies to a control sample of field galaxies, which are matched in the total SFR, \( M_*, \) stellar surface density and redshift.

We showed that galaxies under stronger RPS also have faster HI removal and more enhanced central SFR (compared to general galaxies with similar global SFR). The trend holds for both infalling and virialized galaxies, and in both low-mass and high-mass clusters, which implies that the parameter successfully indicates the RPS strength. Because the weak-RPS is likely to extend beyond \( R_{200} \) for a significant fraction of HI-rich, infalling galaxies, processing and pre-processing may not have a clear border at \( R_{200} \) for the most massive clusters. Because it works in a wide cluster-centric radial range, weak RPS may play a significant role in galaxy evolution in massive clusters. Our parameter of RPS strength brings observables closer to theoretical models of RPS, which may help to disentangle RPS from other environmental effects on galaxy evolution in future applications.

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Appendix A

More Information about the Strong-RPS Galaxies

A.1. The SDSS Atlas

We present in Figure 9 the SDSS (DR7) false-color atlas for all strong-RPS galaxies in the main sample. We also present in Figure 10 the false-color atlas for the three galaxies that can be classified as the strong-RPS type, but excluded for not having enough control galaxies. We find asymmetric distribution of blue light indicative of perturbation on the gas in a few extreme galaxies (e.g., galaxy with ID = 1 in Figure 9, and the first galaxy in Figure 10). In general, it is hard to see morphological features indicative of RPS from these images, for the (g, r, and i-band) optical light is dominated by the old stars that are little influenced by the RPS. The clearest characteristic in the morphology is that these galaxies are disk-dominated (except for the galaxy in the right-hand panel of Figure 10, see discussion in Section 4), which is consistent with the sample selection for HI-rich galaxies.

A.2. The ALFALFA HI Spectrum

We present in Figure 11 the HI spectrum from ALFALFA for all strong-RPS galaxies in the main sample. There are

![Figure 9. SDSS false-color (g, r and i-band) atlas of strong-RPS galaxies in the main sample. The first 17 galaxies are in high-mass clusters and the last three galaxies are in low-mass clusters. All images are 100 arcsec in width.](image-url)
some galaxies with strongly lopsided HI emission lines (e.g., ID = 14, 18, 20), but there are also symmetric galaxies (e.g., ID = 1, 2, 3). Whether the asymmetry of an integral HI line shape reflects the perturbation of the disk depends on the galactic inclination and the signal-to-noise ratio of the spectrum (Watts et al. 2020). Calibration against a sample of solidly confirmed RPS galaxies (either in observation or in simulation) may be needed in the future regarding whether/how information about RPS can be drawn from the integral spectral shape.

A.3. Cross-matching to Nearby Galaxies known with RPS Tails

Among the 17 strong-RPS galaxies in the main sample, four galaxies indeed show RPS features in various image observations (HI, Hα, and u-band optical images, Gavazzi et al. 2001; Scott et al. 2010; Yagi et al. 2017; Roberts & Parker 2020). Particularly, CGCG 097-073 in Abell 1367 cluster (No. 1 in Figure 9) has long, extended ionized (Hα) gas tail due to ram pressure (Gavazzi et al. 2001; Yagi et al. 2017). In addition, the asymmetric HI distribution of CGCG 097-073 suggests that this galaxy is undergoing strong RPS (Scott et al. 2010). Three
galaxies (GMP 5821, GMP 3253, GMP 597, corresponding to No. 10, 12, and 14 in Figure 9) in Coma cluster are visually classified into potential RPS galaxies, based on CFHT u-band images. The u-band images of three galaxies show RPS features such as asymmetric star formation and tails (Roberts & Parker 2020).

Among the three strong-RPS galaxies in high-mass clusters excluded due to insufficient number of control galaxies (Figure 10), J141313.3+200017 (CGCG 097-079 in Abell 1367 cluster) also has an extended ionized gas tail (Gavazzi et al. 2001; Yagi et al. 2017), as CGCG 097-073 does. Its Hφ peak is off from the optical center toward the ionized gas tail (Scott et al. 2010). J130354.4+281837 (GMP 713 in Coma cluster) has been reported as an RPS candidate by visual inspection of the u-band image (Roberts & Parker 2020). However, J125629.79+275622.9 (NGC 4817), an early-type galaxy, has no signature of the RPS effect reported so far.

We note that, not all the galaxies displaying RPS tails in the literature are identified by our method as strong-RPS galaxies, mostly due to our selection criteria. For example, source J125628.57+271728.6, J125809.23+284230.9 and J125839.95+264534.3 in the Coma cluster are identified as RPS candidates by Roberts & Parker (2020). The former two galaxies also show marginally asymmetric Hφ disks (Bravo-Alfaro et al. 2001). They were excluded from our main sample because they have \( R_{\text{HI}} < R_{\text{25}} \), and should be at a relatively later stage of gas depletion. Another known example galaxy of this type is NGC 4569 in the Virgo cluster (Chung et al. 2009; Boselli et al. 2018).

The last galaxy among the three literature candidates was identified as a weak-RPS galaxy by our method.

Appendix B

Test the Classification Method with VIVA HI Images

We take the HI interferometric data of Virgo cluster galaxies observed in the VIVA project (Chung et al. 2009). We derive \( \Sigma_{\text{HI}} \) radial profiles and \( R_{\text{HI}} \) from these HI images. We also use the SDSS photometric measurements from the Extended Virgo Cluster Catalog (Kim et al. 2014), to derive \( M_\odot \) and the optical scale-length \( R_d \). \( M_\odot \) is estimated from the \( r \)-band luminosity and the \( g - r \) color, using the formula from Zibetti et al. (2009). \( R_d \) is estimated as \( R_{50}/1.678 \), assuming an exponential radial distribution.

We select galaxies with \( M_\odot < 10^{11} M_\odot \), \( R_{\text{HI}} > R_{\text{25}} \), and \( R_{25} > 2b_{\text{maj}} \) as for the main sample, but we do not apply the selection criteria on \( \Delta V_{\text{rad}} \) or \( \rho_{\text{maj}} \). This results in 16 galaxies. We note that due to the lower distance of Virgo, VIVA reaches lower \( M_{\text{HI}} \) and \( M_\odot \) limits than our main sample. We use the same set of cluster parameters as in Yoon et al. (2017) to derive ram pressure and the PSD.

A figure of comparing the predicted to the real \( R_{\text{HI}} \) of the VIVA galaxies can be found in Wang et al. (2016, W16). The two types of \( R_{\text{HI}} \) are close to each other, with a median offset of 0.05 ± 0.09 dex. We present in Figure 12 the comparison between real and predicted \( \Sigma_{\text{HI,R25}} \), along with that of normal late-type galaxies from the sample of W16. Despite the good correlation (with Pearson correlation coefficients of 0.8 and 0.89 for the W16 sample and VIVA sample respectively) and relatively small scatter in the offsets between the measured and predicted \( \Sigma_{\text{HI,R25}} \) (0.12 dex and 0.16 dex for the W16 sample and VIVA sample respectively), we notice a saturation of the predicted \( \Sigma_{\text{HI,R25}} \) at \( \sim 6.3 M_\odot pc^{-2} \). Such a saturation typically happens when the galaxy is highly HI-rich and the ratio of \( R_{\text{HI}}/R_{\text{25}} > 2.5 \), so that \( R_{25} \) reaches the inner non-exponential part of the median \( \Sigma_{\text{HI}} \) profile that has a much larger scatter than the outer part (see Figure 2 of W16, and Figure 1 of Wang et al. 2020). The saturation tends to underestimate \( \Sigma_{\text{HI,R25}} \) and thus the anchor force at \( R_{25} \), potentially rendering galaxies to be mistakenly identified into the strong-RPS type. Luckily, because HI richness tends to drop while RPS strength grows, this type of HI-rich galaxies is rare within massive clusters when the ram pressure starts to work and none of our strong-RPS galaxies have \( R_{\text{HI}}/R_{\text{25}} > 2.5 \). So this problem of saturation in the predicted \( \Sigma_{\text{HI,R25}} \) does not significantly affect the estimate of RPS strengths or the results in this paper.

We use the directly measured and predicted \( \Sigma_{\text{HI}} \) radial distributions respectively, and make two sets of classifications that divide galaxies into the strong, weak and no-RPS types. We compare the two sets of classifications on the PSD of the Virgo cluster (Figure 13), and find them to be identical. This strongly supports our classification based on predicted \( \Sigma_{\text{HI}} \). We also see from Figure 13 that most of the galaxies (12/19) are classified into the strong-RPS type, which is consistent with the generally perturbed HI morphologies reported before for the sample (Chung et al. 2009). As discussed in Sections 3.1 and 5.3, our classification method is only applicable to statistical samples, but it is inappropriate to discuss individual sources. We refer the readers to Yoon et al. (2017) for a comprehensive discussion about the statistical correspondence between the perturbed HI morphologies and the PSD positions for the VIVA galaxies.
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**Virgo**

Figure 13. VIVA galaxies in the PSD, which is similar to the bottom panels of Figure 2 but for galaxies from the VIVA sample. The classification of galaxies into strong (red), weak (green) and no (purple) RPS types is based on predicted and observed $\Sigma_{HI}$ radial distributions in the top and bottom panel, respectively.

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**Figures**

- [Figure 2](#): [Link to Figure 2](https://example.com/figure2)
- [Figure 13](#): [Link to Figure 13](https://example.com/figure13)

- **Table 1**
  - [Link to Table 1](https://example.com/table1)

**Notes**

- **Equation 1**: $\Sigma_{HI} = \frac{M_{HI}}{R_{vir}}$
- **Equation 2**: $\Sigma_{HI} = \frac{M_{gas}}{R_{vir}}$

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