A Phase-space View of Cold-gas Properties of Virgo Cluster Galaxies: Multiple Quenching Processes at Work?

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Abstract

We investigate the cold-gas properties of massive Virgo galaxies (>10^9 M_☉) at <3R_{200} (R_{200} is the radius where the mean interior density is 200 times the critical density) on the projected phase-space diagram with the largest archival data set to date to understand the environmental effects on galaxy evolution in the Virgo cluster. We find lower H I and H_2 mass fractions and higher star formation efficiencies (SFEs) from H I and H_2 in the Virgo galaxies than in the field galaxies for matched stellar masses; the Virgo galaxies generally follow the field relationships between the offset from the main sequence of the star-forming galaxies [Δ(MS)] and the gas fractions and SFEs, to the slight offset to lower gas fractions or higher SFEs compared to field galaxies at Δ(MS) < 0; lower gas fractions in galaxies with smaller clustercentric distance and velocity; and lower gas fractions in the galaxies in the W cloud, a substructure of the Virgo cluster. Our results suggest the cold-gas properties of some Virgo galaxies are affected by their environment at least at 3R_{200} maybe via strangulation and/or pre-processes, and H_1 and H_2 in some galaxies are removed by ram pressure at <1.5R_{200}. Our data cannot rule out the possibility of other processes such as strangulation and galaxy harassment accounting for gas reduction in some galaxies at <1.5R_{200}. Future dedicated observations of a mass-limited complete sample are required for definitive conclusions.

Unified Astronomy Thesaurus concepts: Galaxy environments (2029); Virgo Cluster (1772); Molecular gas (1073); Interstellar atomic gas (833)

1. Introduction

As the large-scale structure of the universe develops with time, the environmental effects on galaxies, especially the quenching of star formation activity, are getting more and more important (Peng et al. 2010; Darvish et al. 2016). It has been shown that galaxies in dense regions in the local universe tend to be red and passive (Dressler 1980; Gómez et al. 2003; Balogh et al. 2004; Hogg et al. 2004; Kauffmann et al. 2004; Baldry et al. 2006) and the red and passive galaxy fraction in cluster environments increases with time (Butcher & Oemler 1984; Couch & Sharples 1987; Rakos & Schombert 1995; Ellingson et al. 2001; Marzler et al. 2001; Kodama & Bower 2001; Saintonge et al. 2008; Webb et al. 2013).

In the cluster environment, several processes that are not effective for galaxies in low-density regions (hereafter field galaxies) are considered to become relatively important in galaxy evolution, such as ram pressure stripping (e.g., Gunn & Gott 1972) by intracluster medium (ICM), galaxy harassment (e.g., Moore et al. 1996), and strangulation (e.g., Larson et al. 1980). It has also been claimed that the star formation in galaxies had already been suppressed before they entered the cluster potential, when they were members of a galaxy group that would eventually merged into the cluster (i.e., pre-process; e.g., Fujita 2004).

To understand the quenching processes working on cluster galaxies, it is essential to investigate the physical properties of their cold-gas (atomic and molecular gas) reservoir, which is the raw material for star formation. Recent detailed observations in H I and CO of the so-called Jellyfish galaxies have provided us with an important insight into the effect of ram pressure stripping on the cold gas in galaxies. The Jellyfish galaxies are characterized by their fascinating ionized-gas tails extending from the galaxy and considered to be in the peak phase of ram pressure stripping (Ebeling et al. 2014). They are found to be molecular-gas rich in the tail, and the length of the tail and the velocity gradient along the tail suggest that most molecular gas is formed in situ from atomic gas or diffuse molecular gas rather than stripped from the galaxy as molecular gas (Jáchym et al. 2014, 2017, 2019; Moretti et al. 2018, 2020a, 2020b). Given the depletion time of cold gas by star formation in the tail, which is longer than the Hubble time, the cold gas is considered to become ICM before being consumed by star formation (Jáchym et al. 2014, 2017; Verdugo et al. 2015; Moretti et al. 2018, 2020a). The main body of the Jellyfish galaxies is reported to be atomic-gas poor (Ramatsoku et al. 2019, 2020; Deb et al. 2020), molecular-gas rich (Moretti et al. 2020), and actively forming stars, suggesting that ram pressure stripping promotes molecular-gas formation from atomic gas and consequently star formation in galaxies. After this phase, star formation activity in galaxies is expected to be quenched.
For a more general view of the cold-gas properties in cluster galaxies, the atomic-gas deficit is reported to be ubiquitous in the cluster environment in various observational studies of nearby clusters, such as the Virgo cluster (Davies & Lewis 1973; Chamaraux et al. 1980; Cayatte et al. 1990; Solanes et al. 2001; Gavazzi et al. 2005), the Coma cluster (Gavazzi et al. 2006; Healy et al. 2021), the Fornax cluster (Schröder et al. 2001; Waugh et al. 2002), and a combination of multiple clusters (Solanes et al. 2001; Brown et al. 2017).

On the other hand, no definitive conclusion has been reached for whether or not the cluster environment affects the molecular-gas content of galaxies. In the local universe, contradicting results have been reported in different clusters and even in the same clusters. For example, a CO deficit in cluster galaxies is reported for the Virgo cluster (Rengarajan & iyengar 1992; Fumagalli et al. 2009; Corbelli et al. 2012; Boselli et al. 2014b), the Coma cluster (Fumagalli et al. 2009), the Fornax cluster (Zabel et al. 2019), and the A262 cluster (Bertram et al. 2006). In contrast, no significant difference in CO content between field and cluster galaxies is reported for the Virgo cluster (Kenney & Young 1986, 1989; Stark et al. 1986; Boselli 1994; Perea et al. 1997; Nakamishι et al. 2006; Chung et al. 2017), the Coma cluster (Casoli et al. 1991; Boselli et al. 1997), and the Antlia cluster (Cairns et al. 2019). Mok et al. (2017) found that molecular gas is even more abundant in Virgo galaxies than in the field counterparts. However, based on detailed mapping observations toward individual galaxies in the Virgo cluster, it has been shown that there certainly exist galaxies whose molecular gas is being stripped by the ram pressure (e.g., NGC 4330, NGC 4402, NGC 4438, NGC 4522; Combes et al. 1988; Vollmer et al. 2008, 2009, 2012; Lee et al. 2017; Cramer et al. 2020).

It is not obvious that all galaxies in a cluster with different masses and evolutionary stages are experiencing quenching processes in the same way. In addition, there should be various galaxies under different kinds and levels of quenching processes even within a cluster. Molecular gas is unlikely to be as easily stripped as atomic gas (e.g., Kenney & Young 1986; Cortese et al. 2016; Jáchym et al. 2017), considering that the atomic-gas disk typically extends out to a few (or more) times the size of the optical disk (e.g., Warren et al. 2004; Koribalski & López-Sánchez 2009; Koribalski et al. 2018), whereas the molecular-gas disk is confined within 50% of the optical disk (Young et al. 1995), where the anchoring force per area is strong against the ram pressure. Simply comparing field and cluster galaxies does not give us a clear conclusion on the molecular deficiency of cluster galaxies.

The clustocentric distance is one of the measures of the time since the first infall to the cluster (accretion phase) and has been used to investigate galaxy properties (e.g., Anderssen 1996; Coenda & Muriel 2009; Coenda et al. 2009; Sheen et al. 2012; Gu et al. 2013, 2016), although the projected distance alone is not enough because there could be galaxies located at various clustocentric distances along the line of sight (Smith et al. 2015). If the clustocentric distance and clustocentric velocity are considered simultaneously, i.e., the so-called “phase-space diagram” (PSD), it has been claimed that it possible to classify galaxies according to their accretion phase (e.g., Mahajan et al. 2011; Oman et al. 2013; Rhee et al. 2017) and the degree of tidal mass loss (e.g., Smith et al. 2015; Rhee et al. 2017) based on numerical simulations. Many observational studies find that galaxies in different locations on the PSD have different properties, such as morphology, stellar mass, star formation, active galactic nucleus activity, and dust temperature (Biviano et al. 2002; Mahajan et al. 2011; Noble et al. 2013, 2016; Pimbblet et al. 2013; Hernández-Fernández et al. 2014; Muzzin et al. 2014).

The cold-gas properties of galaxies on the PSD have also been investigated. H I gas observations toward cluster galaxies showed that galaxies that are expected to be affected by ram pressure on the PSD tend to have lower levels of atomic gas than field galaxies (Jaffé et al. 2015; Wang et al. 2020). Yoon et al. (2017) investigated a relationship between H I morphology, as a measure of the ram pressure stripping, and the location on the PSD of Virgo galaxies and showed that galaxies with severely stripped H I disks are found deep inside the cluster. For molecular-gas properties on the PSD, on the other hand, there is no systematic study in nearby clusters but in distant clusters at $z \sim 1.5-2.5$ (e.g., Hayashi et al. 2017; Wang et al. 2018). Wang et al. (2018) clearly showed that molecular-gas properties are correlated with the accretion phase in the cluster, where those closer to the cluster center and those with a smaller relative velocity to the cluster tend to be increasingly gas poor.

In this work, we investigate both the atomic- and molecular-gas and star formation properties of the Virgo galaxies in the PSD with the largest CO and H I data so far by combining several data sets from the literature in order to understand the environmental effects on these galaxy properties. The Virgo cluster is the nearest massive galaxy cluster to the Milky Way and therefore provides abundant multiwavelength data. The cluster is considered to be a dynamically young system (Arnaboldi et al. 2004; Aguerri et al. 2005), contains a relatively high fraction of blue spiral galaxies (Cappellari 2013), and shows an asymmetric structure of hot ICM traced in X-ray (Böhringer et al. 1994).

The structure of the paper is as follows: we first introduce our sample and the data used in this study in Section 2. We present our results on the cold-gas and star formation properties of the Virgo galaxies in Section 3 and briefly summarize the results in Section 4. The environmental effects on cold-gas and star formation properties of Virgo galaxies are discussed in Section 5. Finally, we present our conclusions in Section 6. We adopt the coordinates of M 87, the brightest cluster galaxy in the Virgo cluster, $(\alpha, \delta) = (12^h30^m49.4, +12^\circ23'28'')$, as the cluster center; a distance of 16.5 Mpc (Mei et al. 2007); the $R_{500}$, the radius where the mean interior density is 200 times the critical density, of 5.38 Mpc (McLaughlin 1999); a velocity dispersion of 800 km s$^{-1}$ (Binggeli et al. 1993); and the initial mass function (IMF) of Chabrier (2003) throughout this paper.

2. Sample and Data

We adopted the Extended Virgo Cluster Catalog (EVCC; Kim et al. 2014), containing SDSS optical data of 1589 galaxies, as a reference list of Virgo galaxies, then searched for their stellar mass ($M_{\text{star}}$), star formation rate (SFR), H I and CO data. In this section, we first mention the reference galaxies for the cross-match especially in terms of the membership to the Virgo cluster in Section 2.1. Then we describe the cross-matches with the literature and the derivation of each physical quantity in Section 2.2 for $M_{\text{star}}$ and SFR, Section 2.3 for molecular-gas mass ($M_{\text{H2}}$), and Section 2.4 for atomic-gas mass ($M_{\text{HI}}$). The cross-match summary is presented in Section 2.5, and we introduce key quantities adopted in this study to investigate star formation and cold-gas properties of galaxies in Section 2.6. In Section 2.7, we describe several subsamples
measurements (H I measurements comparison with a cluster infall model \(\sim\) tively. The mean velocity of these W and M cloud galaxies is partially and largely categorized as possible members, respec-
to the EVCC classi

\[\text{X-ray image} \quad \text{categories in terms of their membership to the Virgo cluster, multiple detections.}\]

treated in this study. For galaxies with multiple CO or H I measurements, we prioritize data with detections rather than upper limits, and calculate error-weighted means in case of multiple detections.

2.1. Membership to the Virgo Cluster and Substructures

In the EVCC, the listed galaxies are categorized into two categories in terms of their membership to the Virgo cluster, “secure” and “possible” members, based on the redshift comparison with a cluster infall model (Kim et al. 2014). It is known that there are several substructures in the Virgo cluster (Figure 1(a), Binggeli et al. 1985, 1987, 1993; Sandage et al. 1985): A (or M87) cluster, B (or M49) cluster, NGC 4636 group, M cloud (Ftaclas et al. 1984), W’ cloud (de Vaucouleurs 1961), and W cloud (de Vaucouleurs 1961). Additionally, the galaxies at decl. less than 5° are called the “southern extension.” According to the EVCC classification, galaxies in the W and M clouds are partially and largely categorized as possible members, respectively. The mean velocity of these W and M cloud galaxies is \(\sim 2000 \text{ km s}^{-1} \) (\(\sim 1000 \text{ km s}^{-1}\) for the main body of the Virgo cluster), and they are considered to be located at twice the distance of the Virgo cluster (Binggeli et al. 1993). The M and W clouds galaxies are also categorized as possible members in the classical Virgo Cluster Catalogue (Binggeli et al. 1985).

On the other hand, Yoon et al. (2012) and Yoon & Putman (2017) found that Lyc-absorbing warm-hot gas (\(T = 10^4-10^6 \text{ K}\)) is associated with substructures in the Virgo cluster including both the M and W clouds, and suggested that the observed warm gas is part of large-scale gas flows into the Virgo cluster. Such warm-hot gas is preferentially found in the outskirts rather than the central region of galaxy clusters (Yoon et al. 2012; Yoon & Putman 2017; Burchett et al. 2018), which is also predicted in hydrodynamic simulations of the galaxy clusters (Emerick et al. 2015), although the mass contribution of the warm-hot gas is not that large compared to the X-ray-emitting hot gas (\(\sim 3\%\); Burchett et al. 2018). Thus, we use both the secure and possible members of the Virgo cluster in the following analysis. The effect of the inclusion of possible members on our results is discussed in Section 5.1.

2.2. Stellar Mass and Star Formation Rate

For the \(M_{\text{star}}\) and SFR data, the EVCC is cross-matched with the sample galaxies in the project “z = 0 Multiwavelength Galaxy Synthesis” (z0MGS; Leroy et al. 2019), resulting in 721 galaxies. Leroy et al. (2019) measured the \(M_{\text{star}}\) and SFR of \(\sim 15,750\) galaxies located at \(<50 \text{ Mpc}, which are observed with the Galaxy Evolution Explorer (GALEX; Martin et al. 2005) and the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010). The z0MGS project derived an empirical relationship between \(M_{\text{star}}\) and WISE photometry at 3.4 \(\mu\text{m}, and SFR and WISE (22 \(\mu\text{m}\)) and GALEX (far-ultraviolet or near-ultraviolet) photometry using data obtained in the GALEX–SDSS–WISE Legacy Catalog (GSWLC; Salim et al. 2016). Leroy et al. (2019) prioritize a “hybrid” SFR estimation for galaxies that are observed and detected both with GALEX and WISE, i.e., SFR estimation with ultraviolet and mid-infrared data to account for both the obscured and unobscured components. The GSWLC project combined GALEX and WISE photometry with SDSS observations and conducted population synthesis modeling using the CIGALE code (Boquien et al. 2019). Salim et al. (2016) assumed a Chabrier IMF to derive \(M_{\text{star}}\) and SFR (Chabrier 2003).

2.3. Molecular Gas Mass

For the CO data, we used the literature data of Boselli et al. (1995), Chung et al. (2009b), Atlas 3D (Young et al. 2011), the
Analysis of the interstellar Medium in Isolated GAlaxies (AMIGA; Lisfenfeld et al. 2011), the Herschel Reference Survey (HRS; Boselli et al. 2014a), and CO Multi-line Imaging of Nearby Galaxies (COMING; Sorai et al. 2019) and found 186 galaxies (175 with $M_{\text{star}}$ and SFR measurements) without double counting. $M_{\text{Hi}}$ is calculated from CO line luminosity ($L_{\text{CO}}^{14}$) with a CO-to-H$_2$ conversion factor for the Milky Way ($\alpha_{\text{CO}} = 3.21 M_{\odot} [\text{K km s}^{-1} \text{pc}^2]^{-1}$), which corresponds to $X_{\text{CO}} = 2.0 \times 10^{20} \text{cm}^{-2} [\text{K km s}^{-1}]^{-1}$ as

$$M_{\text{Hi}} = 1.36 \times \alpha_{\text{CO}} L_{\text{CO}}^{14},$$

where a factor of 1.36 accounts for the helium contribution to mass (e.g., Bolatto et al. 2013). Here we do not consider the metallicity dependence of $\alpha_{\text{CO}}$ because our sample galaxies are massive galaxies whose $M_{\text{star}}$ are larger than $\sim 10^9 M_{\odot}$, which is near the turnover mass for the mass–metallicity relation of local galaxies (Andrews & Martini 2013) and roughly corresponds to the solar metallicity (12 + log(O/H) = 8.69, Asplund et al. 2009). At metallicities larger than the solar value, the variation in $\alpha_{\text{CO}}$ is small (Figure 9 of Bolatto et al. 2013). Additionally, it has been claimed that the mass–metallicity relation of galaxies does not strongly depend on the galaxy environments and the metallicity of cluster galaxies is found to be slightly higher than that of field galaxies ($\sim 0.05$ dex; e.g., Mouchine et al. 2007; Cooper et al. 2008; Ellison et al. 2009).

### 2.4. Atomic-gas Mass

For the H I data, we cross-matched the EVCC galaxies with literature data obtained in The Arecibo Legacy Fast ALFA survey (ALFALFA; Giovanelli et al. 2005), Atlas 3D (Serra et al. 2012), and VLA Imaging of Virgo Spirals in Atomic Gas (VIVA, Chung et al. 2009a), resulting in 570 galaxies (271 with $M_{\text{star}}$ and SFR measurements) without double counting. $M_{\text{atom}}$ is calculated based on the optically thin assumption as

$$M_{\text{HI}} = 1.36 \times 2.36 \times 10^5 D^2 \times \Sigma S \Delta \nu,$$

where the factor of 1.36 again accounts for the helium contribution to mass, $D$ is the distance to the galaxies in Mpc, and $\Sigma S \Delta \nu$ is the summation over the total emission in each channel in Jy km s$^{-1}$ (e.g., Wild 1952).

### 2.5. Cross-match Summary

The sky distribution of the secure/possible member galaxies in the EVCC is shown in Figure 1, and the cross-match summary is presented in Table 1. Table 2 summarizes the subsamples in this study. Figure 2 shows the color–magnitude relation of target galaxies in this study and the EVCC galaxies with data of the Sloan Digital Sky Survey (SDSS) Data Release 7 (DR7; Abazajian et al. 2009). We can see that our sample galaxies are biased to bright objects, or massive galaxies that are expected to be less affected by their environments than less massive galaxies (Peng et al. 2010). Our main target is limited to massive galaxies with $M_{\text{star}} > 10^9 M_{\odot}$, which is the lowest $M_{\text{star}}$ value of field samples for comparison (see Section 3.1). The completeness of our sample with $M_{\text{star}} > 10^9 M_{\odot}$ is $\sim 65\%–90\%$ at absolute $r$-band magnitudes of $\lesssim -16.7$ mag (see the histograms in Figure 2).

### 2.6. Key Quantities

With the physical values estimated above, we can calculate the following key quantities of galaxies: specific SFR ($\text{sSFR} = \text{SFR}/M_{\text{star}}$), atomic-gas mass fraction ($\mu_{\text{HI}} = M_{\text{HI}}/M_{\text{star}}$), molecular-gas mass fraction ($\mu_{\text{H}_2} = M_{\text{H}_2}/M_{\text{star}}$), total gas mass fraction ($\mu_{\text{gas}} = (M_{\text{HI}} + M_{\text{H}_2})/M_{\text{star}}$), molecular-gas to atomic-gas mass ratio ($R_{\text{H}_2} = M_{\text{H}_2}/M_{\text{HI}}$), star formation efficiency (SFE) from atomic gas (SFE$_{\text{HI}} = \text{SFR}/M_{\text{HI}}$), SFE
from molecular gas (SFE$_{\text{HI}} = $ SFR/\(M_{\text{HI}}\)), and SFE from total gas (SFE$_{\text{gas}} = $ SFR/\(M_{\text{gas}}\)).

### 2.7. Subsamples

In the following sections, we compare the key quantities of Virgo galaxies on a best-effort basis, i.e., we use all of the galaxies with measurements including both detections and upper limits and all of the numerators and denominators of the key quantities (hereafter, best-effort sample), and thus the number of galaxies in each plot is different depending on the quantities. To assess the sample bias due to this treatment, we also compute these values for galaxies with all the measurements of \(M_{\text{star}}\), SFR, H I, and CO (CO+H I-obs. sample, 113 galaxies) or galaxies with detections (CO+H I-det. sample, 70 galaxies) (see Table 2).

#### Table 2

| Subsample                  | Matched | Detected |
|----------------------------|---------|----------|
| H$_2$                      | 132/54  | 75/26    |
| H I                        | 353/217 | 318/215  |
| H$_2$ & H I                | 94/24   | 49/14    |
| H$_2$ & z0MGS              | 122/53  | 68/25    |
| H I & z0MGS                | 169/102 | 134/100  |
| H$_2$ & H I & z0MGS        | 90/24   | 46/14    |
| H$_2$,\(M_{\text{star}}\)  | 121/52  | 68/25    |
| H$_1$,\(M_{\text{star}}\)  | 124/70  | 89/68    |
| H$_2$,\(M_{\text{star}}\) & H I,\(M_{\text{star}}\) | 90/23$^b$ | 46/14$^b$ |

**Notes.**

$^a$ Galaxies with \(M_{\text{star}} > 10^{10} M_{\odot}\), i.e., with \(\Delta\) (Field) measurements.

$^b$ CO+H I-obs. sample.

$^c$ CO+H I-det. sample.

From Figure 2, Cross-match result between EVCC and the literature: color-magnitude relations and the completeness of each subsample as a function of \(r\)-band magnitude for (a) the galaxies without an \(M_{\text{star}}\) cut and (b) those with \(M_{\text{star}} > 10^9 M_{\odot}\). The gray contour in both panels indicates all of the EVCC galaxies. The galaxies with \(M_{\text{star}}\) and SFR, H I, and CO measurements including upper limits are indicated as filled gray circles/triangles for the secure/possible members, orange X marks, and blue open square, respectively. Black filled symbols indicate galaxies with \(M_{\text{star}} > 10^9 M_{\odot}\), which are the main targets in this study. The dashed and dotted lines indicate the red sequence and the blue cloud of local SDSS galaxies (Baldry et al. 2004). The fractions of galaxies listed in the z0MGS (gray), those with \(M_{\text{star}} > 10^9 M_{\odot}\) (black), those with H I measurements (orange), and those with CO measurements (blue) among the EVCC are also shown in the upper panels of each plot.

#### Figure 3

Numbers of Secure/Possible Virgo Members for Each Subsample

Figure 3 shows the \(M_{\text{star}}\) distribution of our seven subsample galaxies with \(M_{\text{star}} > 10^9 M_{\odot}\), such as (a) galaxies with H I and CO measurements (CO+H I-obs. sample), (b) galaxies with H I measurements, (c) galaxies with CO measurements, (d) galaxies with \(M_{\text{star}}\) and SFR measurements, (e) galaxies with H I and CO detections (CO+H I-det. sample), (f) galaxies with H I detections, and (g) galaxies with CO detections. The best-effort sample consists of (a) \(\mu_{\text{gas}}, \text{SFE}_{\text{gas}}, \text{and } R_{\text{HI}}, \) (b) \(\mu_{\text{HI}}, \) and \(\text{SFE}_{\text{HI}}, \) (c) \(\mu_{\text{HI}}\) and \(\text{SFE}_{\text{HI}}, \) and (d) SFR and ssSFR.

The \(\log(M_{\text{star}}/M_{\odot})\) medians of the field and Virgo galaxies and the p-value of the KS test are also presented in each panel (see Section 3.1 for the field sample). The \(M_{\text{star}}\) medians of the field galaxies are larger than those of the Virgo galaxies, and the KS test shows that the difference of the \(M_{\text{star}}\) distribution between the field and the Virgo galaxies is statistically significant. Additionally, the KS test among the different Virgo subsamples shows that the \(M_{\text{star}}\) distribution is different for (a) versus (d), (a) versus (f), (c) versus (d), (c) versus (f), (d) versus (e), and (f) versus (g). The \(M_{\text{star}}\) medians of these subsamples suggest that the galaxies with CO measurements are more massive (\(\sim 10^{10.0} M_{\odot}\)) than those only with \(M_{\text{star}}\) and SFR measurements and those with H I detections (\(\sim 10^{9.7} M_{\odot}\)). Therefore, the best-effort sample in plots for SFR and ssSFR is slightly biased to lower mass systems compared to the other subsamples.
3. Cold-gas and Star Formation Properties

In this section, we focus on the key quantities (sSFR, $\mu_{H_2}$, $\mu_{HI}$, $\mu_{\text{gas}}$, $R_{HI}$, SFE$_{HI}$, SFE$_{H_2}$, and SFE$_{\text{gas}}$) to investigate the relationship between the cold-gas and star formation properties of galaxies and their locations in the Virgo cluster. In this study, we consider that two samples are different when the $p$-value of the KS test becomes less than 0.05. The correlation between two values is assessed based on the Spearman’s rank-order correlation coefficient and the reliability of the correlation coefficient is assessed with the $p$-value, i.e., we consider that two quantities are correlated when the $p$-value is less than 0.05.

We first compare the Virgo galaxies and the field galaxies in Section 3.1 and then investigate the dependence of the key quantities on the clustocentric distance in Section 3.2, on the local galaxy density in Section 3.3, and on the accretion phase in the cluster in Section 3.4.

3.1. Comparison with Field Galaxies

We compare the Virgo galaxies and field galaxies in Figure 4. Note that the left peaks for the gas fractions consist of galaxies with the upper limits. In Appendix A, we also show the comparison of the key quantities of the Virgo and field galaxies without the upper limits (Figure 12). To derive the empirical relationships of key quantities as a function of stellar mass in the field galaxies, we make use of data from the extended GALEX Arecibo SDSS Survey (xGASS; Catinella et al. 2018) for H I-related relations and the extended CO Legacy Database for GASS (xCOLD GASS; Saintonge et al. 2017) for H$_2$-related relations. We adopted the star-forming main sequence (SFMS) galaxies defined in Speagle et al. (2014). The difference between the Virgo and field galaxies [\Delta(Field)] in Figure 4 is calculated as $\Delta(\text{Field}) = \log_{10}(X_{\text{Virgo}}(M_{\text{star}})/X_{\text{Field}}(M_{\text{star}}))$, where $X_{\text{Virgo}}(M_{\text{star}})$ and $X_{\text{Field}}(M_{\text{star}})$ are key quantities for the Virgo and field galaxies at the stellar mass of $M_{\text{star}}$, which are derived based on polynomial regression with an order of three except for SFR and sSFR. Speagle’s SFMS is adopted for $X_{\text{Field}}(M_{\text{star}})$ for SFR and sSFR.

We find that the Virgo galaxies have lower medians of SFR, sSFR, gas fractions, and higher medians of $R_{HI}$ and SFEs than the field galaxies in both cases, that the sample includes those with CO or H I upper limits (best-effort sample; Figure 4), and that the sample is limited to those with CO or H I detections (Figure 12 in Appendix A). These differences are confirmed to be statistically significant according to the KS test. Even in the case where we limit the sample to galaxies with CO and H I measurements, i.e., the CO+H I-obs. sample, the conclusions do not change.

It has been claimed that both the $\mu_{HI}$ and SFE$_{HI}$ values of galaxies are related to the offset from the SFMS of the field galaxies, $\Delta(\text{MS}) = \log_{10}(\text{SFR}/\text{SFR}_{\text{MS}})$, where SFR$_{\text{MS}}$ is the SFR of the SFMS field galaxies for a fixed stellar mass and redshift (e.g., Saintonge et al. 2012; Genzel et al. 2015; Scoville et al. 2017; Ellison et al. 2020). These relations are independent of the local galaxy number density at least for field and group galaxies (Koyama et al. 2017). Figure 5 compares the relationships of $\Delta(\text{MS})$ with cold-gas mass fractions, $R_{HI}$, and SFEs for the Virgo and field galaxies. Although most Virgo galaxies follow the same relation as field galaxies, the Virgo galaxies tend to be distributed at the lower $\Delta(\text{MS})$ regime in these plots. Interestingly, some Virgo galaxies, especially below the main sequence ($\Delta(\text{MS}) \sim -1$), seem to have decreased $\mu_{HI}$ and elevated $R_{HI}$ and SFEs compared to field galaxies for fixed $\Delta(\text{MS})$. We compare the medians of gas fractions, $R_{HI}$, and SFEs of the field and the Virgo galaxies with CO or H I detection depending on the quantities on the SFMS ($-0.5 < \Delta(\text{MS}) < 0.5$) as well as those below the SFMS ($-1.5 < \Delta(\text{MS}) < -0.5$). We find that the Virgo galaxies have
lower gas fractions and higher $R_{H_2}$ and SFEs than the field galaxies both on and below the SFMS. The KS test shows that the differences between the field and the Virgo galaxies are statistically significant for the subsamples below the SFMS. For the SFMS galaxies, only the differences in $\mu_{H_2}$ and $R_{H_2}$ of the Virgo galaxies are lower and higher than those of the field galaxies, respectively. It should be also noted that H I-related values of the Virgo galaxies show a wider variation than the field galaxies at a fixed $\Delta$(MS).

In the following sections, we use the $\Delta$(Field) values, i.e., the values from which $M_{\text{star}}$ dependences of field galaxies have been subtracted, in order to investigate the environmental effect without the $M_{\text{star}}$ effect.

### 3.2. Dependence on the Clustocentric Distance

The galaxy properties as a function of clustocentric distance have been investigated in many previous studies showing that galaxies nearer to the cluster center tend to be more passive and H I deficient (e.g., Giovanelli & Haynes 1985; Solanes et al. 2001). To investigate the radial variation of the galaxy properties, we divided our Virgo galaxies into six radial bins where each bin spans $0.5R_{200}$ as $R_{\text{proj}}/R_{200} < 0.5$ ($R_1$), $0.5 \leq R_{\text{proj}}/R_{200} < 1.0$ ($R_2$), $1.0 \leq R_{\text{proj}}/R_{200} < 1.5$ ($R_3$), $1.5 \leq R_{\text{proj}}/R_{200} < 2.0$ ($R_4$), $2.0 \leq R_{\text{proj}}/R_{200} < 2.5$ ($R_5$), and $R_{\text{proj}}/R_{200} \geq 2.5$ ($R_6$), where $R_{\text{proj}}$ is the projected distance from a galaxy to M87. The outermost galaxy in our best-effort sample is located at $\sim 3R_{200}$.

Figure 6 shows the medians and first and third quartiles of the key quantities for galaxies in each category. There is a
Figure 5. Comparison between the Virgo galaxies and field galaxies with $M_{\text{star}} > 10^7 M_\odot$: relationships between the offsets from the main sequence of star-forming galaxies, $\Delta(\text{MS})$, and gas fractions, $R_{\text{HI}}$, and SFEs. The Virgo galaxies with a H I detection, a H I upper limit, a CO detection, and a CO upper limit are indicated as a filled orange square, open orange square, filled blue circle, and open blue circle, respectively. The field relations are estimated with CO- or H I-detected galaxies, i.e., star-forming galaxies, and indicated with dashed (with nonparametric fitting) and (with third-order polynomial fitting) solid lines in the panels (e)-(i). Gray-shaded regions are the errors of the nonparametric fitting and estimated by the bootstrap method with a 95% confidence interval. The contours indicate field galaxies used to derive the field relations. The lower/upper limits of field galaxies are indicated as open triangles/inverted triangles. For the $R_{\text{HI}}$ panel, the field galaxies with H I and CO upper limits are indicated as X marks.

radial tendency in the SFR and cold-gas fractions in galaxies where these values are lower for galaxies nearer to the cluster center than their counterparts in the outskirts. The Spearman’s rank-order correlation coefficient and the $p$-value confirm that the clustocentric distance positively correlates to SFR, sSFR, and gas fractions with correlation coefficients of 0.3–0.5 and negatively correlates to SFE$_{\text{gas}}$, SFE$_{\text{H}_2}$, and $R_{\text{HI}}$ with correlation coefficients ranging from $-0.4$ to $-0.3$. SFE$_{\text{HI}}$ does not show a clear dependence on the clustocentric distance. Additionally, the radial trends of the gas fractions are not completely continuous but there seems to be a bend between $R_1$ and $R_2$. Note that the galaxies in the W-cloud galaxies are excluded from Figure 6 because the cold-gas and star formation properties are different from the surrounding galaxies. The inclusion of the W-cloud galaxies causes a jump rather than a bend between $R_1$ and $R_4$ in sSFR and $\mu_{\text{HI}}$. Here, the W-cloud galaxies are defined on the PSD by eye, and the definition is presented in Section 3.4. The properties of the W-cloud galaxies are discussed more in Sections 3.4 and 5.2.3. SFEs and $R_{\text{HI}}$ do not show a clear dependence on the clustocentric distance, whereas SFE$_{\text{HI}}$ at $R_3$ is lower than those at the other radii ($p$-values of the $R_3$ versus $R_1$ and $R_4$ versus $R_5$ comparisons are 0.0042 and 0.0019, respectively).

For a comparison with the field galaxies (zero corresponds to the values of field galaxies), we can see that gas fractions, $R_{\text{HI}}$, SFE$_{\text{gas}}$, and SFE$_{\text{H}_2}$ are already comparable to field galaxies at $>R_5$ whereas the medians of the SFR and sSFR are slightly lower than those of the field galaxies. On the other hand, SFE$_{\text{HI}}$ tends to be higher than the field galaxies even at $>R_5$.

Note that the same tendency is observed even when we consider only the sample with CO and H I measurements, i.e., the CO+H I-obs. sample. If we limit the sample to galaxies with CO and H I detection (CO+H I-det. sample), the radial trends seen in SFR, sSFR, and gas fractions disappear.

### 3.3. Dependence on the Galaxy Number Density

Galaxy number density is one of the important parameters to understand the dominant quenching mechanism in cluster galaxies. If the dominant quenching mechanism is related to the local number density rather than the cluster ICM or potential, galaxy–galaxy interactions are expected to be important.

We adopt two distances to see the dependences of the key quantities on the local galaxy density: the distances to the fifth nearest galaxy (1) on the sky ($R_{5,\text{sky}}$) and (2) on the PSD ($R_{5,\text{PSD}}$), where the vertical and horizontal axes are, respectively, $R_{\text{proj}}/R_{200}$ and $\Delta V_{\text{gal}}/\sigma_{\text{Virgo}}$, and both values are dimensionless quantities ($\Delta V_{\text{gal}}$ is the velocity difference between a galaxy and M87). We make use of these two values complementarily to evaluate the effect of galaxy–galaxy interactions including the galaxy harassment (multiple high-speed galaxy–galaxy encounters) because some galaxy pairs can have a smaller $R_{5,\text{sky}}$ by chance even though the actual distance between them along the line of sight would be much larger than the projected distance, which can dilute the true relations between $R_{5,\text{sky}}$ and the key quantities. On the other hand, the comparison with $R_{5,\text{PSD}}$ would miss the effect of galaxy harassment.

First, we compare $R_{5,\text{sky}}$ or $R_{5,\text{PSD}}$ with the projected clustocentric distance (plots are shown in Figure 13 of Appendix B). Overall, there are moderate and weak positive correlations between $R_{5,\text{sky}}$ and $R_{5,\text{PSD}}$ with the clustocentric distance.
Figure 6. Radial variation of key quantities (median and the first and third quartiles) whose $M_{\text{vir}}$ dependence have been subtracted, i.e., $\Delta(\text{Field})$ values. The individual data are indicated as gray filled circles. The zero of each key quantity indicates the values of the field galaxies (dashed line), and the gray-shaded regions indicate the 1σ of the $\Delta(\text{Field})$ values for the field galaxies. Note that the numbers of galaxies used to plot in each panel are different. The Spearman’s rank-order correlation coefficient $r$ and the $p$-value are shown on the lower-left corner of each panel in purple. The W-cloud galaxies that are mostly in the $R_3$ bin are excluded from this plot.
distance, respectively. The obtained positive correlations suggest that the dependence of the key quantities on clustocentric distance seen in Figure 6 might just reflect the dependence on the local densities and vice versa. The exclusion of the W-cloud galaxies increases $R_{5,\text{sky}}$ and $R_{5,\text{PSD}}$ at the $R_3$ bin but does not drastically change the overall trend.

Next, we compare $R_{5,\text{sky}}$ or $R_{5,\text{PSD}}$ with the key quantities. Plots for $R_{5,\text{sky}}$ and $R_{5,\text{PSD}}$ are shown in Figures 7 and 14 in Appendix B, respectively. We observe positive correlations between $R_{5,\text{sky}}$ and SFR, $sSFR$, and gas fractions with correlation coefficients of $\sim 0.3$–$0.4$, and negative correlations with $SFE_{\text{gas}}$ and $SFE_{\text{HI}}$ with a correlation coefficient of $\sim -0.3$. In the case of $R_{5,\text{PSD}}$, we find positive correlations with SFR, $sSFR$, and $\mu_{\text{HI}}$ with correlation coefficients of $\sim 0.2$. The exclusion of the W-cloud galaxies basically does not change the results for $R_{5,\text{sky}}$ and $R_{5,\text{PSD}}$. On the other hand, for the $R_{5,\text{PSD}}$, the correlation with $\mu_{\text{HI}}$ becomes insignificant when excluding the W-cloud galaxies. If we limit the sample to those with both the CO and H I measurements (CO+H I-obs. sample), the results do not change but the correlation between $R_{5,\text{PSD}}$ and $\mu_{\text{HI}}$ becomes insignificant. Next, if we limit the sample to those with both the CO and H I detections (CO+H I-det. sample), all the correlations for $R_{5,\text{sky}}$ and $R_{5,\text{PSD}}$ become insignificant. Therefore, the radial tendency observed in SFR, $sSFR$, and gas fraction can be partially attributed to the radial dependence of the local galaxy density where the local environment of galaxies becomes denser nearer to the cluster center.

### 3.4. Dependence on the Accretion Phase to the Cluster

In order to see the effect of ram pressure, we divide the galaxies into two groups in terms of accretion phase on the projected PSD of the cluster: (1) “virialized” (VIR) and
“stripping” (RPS), (2) “recent infall” (RIF). The RPS and VIR galaxies are respectively expected to be currently affected and to have been affected by the ram pressure, but it turned out that there is no RPS galaxy in our sample. Jaffé et al. (2015) show that on the projected PSD, galaxies oscillate in position and velocity, drawing a “wedge,” and fall into a cluster core in their simulations (galaxy trajectories on the PSD shown in Figure 4 of Jaffé et al. 2015). However, it should be noted that not all galaxies in the VIR region have necessarily experienced ram pressure stripping. The position on the PSD provides a statistical probability that each galaxy is in a different accretion phase and is not univocally associated with the quenching mechanisms. The probability for Milky Way-type galaxies being stripped by ram pressure is estimated to be $\gtrsim 60\%$ in the VIR region of a $z \sim 0.2$ cluster (Figure 6 of Jaffé et al. 2015). The W-cloud galaxies are treated separately from the other RIF galaxies. Figure 8 shows the galaxy distribution on the PSD, color-coded according to the SDSS $(u - r)$ color and the galaxy classification on the PSD.

The classification is basically done following the procedures presented in Jaffé et al. (2015) and Yoon et al. (2017). The VIR region is enclosed by the line connecting the points of $(R_{\text{proj}}/R_{200}, |\Delta v_{\text{gal}}|/\sigma_{\text{Virgo}}) = (1.2, 0.0)$ and $(0.0, 1.5)$. Although there is no RPS galaxy in our sample, the RPS region is determined by the balance between the ram pressure, $P_{\text{ram}} = \rho_{\text{ICM}} v_{\text{3D,gal}}^2$, and the galaxy’s anchoring force per area, $\Pi_{\text{gal}} = 2\pi G \Sigma_{\text{star}} \Sigma_{\text{gas}}$, where $\rho_{\text{ICM}}$, $v_{\text{3D,gal}}$, $G$, $\Sigma_{\text{star}}$, and $\Sigma_{\text{gas}}$ are the ICM density distribution, 3D velocity of the galaxy ($v_{\text{3D,gal}} = \sqrt{3} v_{\text{H2,gal}}$), gravitational constant, and surface mass density of stellar and gas disks, respectively (Gunn & Gott 1972). The ram pressure felt by a member galaxy is a function of the clustercentric velocity of the galaxy and the density distribution of the ICM. On the other hand, the galaxy’s anchoring force per area is a function of surface densities of stellar and gas components at a galactic radius where stripping is active. The adopted boundary line in this study represents a galaxy with a stellar mass of $10^9 M_\odot$ and a scale length of 0.9 kpc (the median value for EVCC galaxies with $M_{\text{star}} \sim 10^9 M_\odot$). This RPS boundary is a measure to assess whether or not the entirety of the gas of a $10^9 M_\odot$ galaxy is stripped by ram pressure, i.e., even the gas at the galaxy center where the anchoring force is the strongest is removed. Generally, cold gas in less massive galaxies tends to be more easily stripped by ram pressure (see Figure 8). The model parameters to calculate a boundary line for the RPS galaxies are summarized in Table 3.

The W-cloud galaxies are defined on the PSD by eye as mentioned in Section 3.2. We consider that galaxies in an ellipse on the PSD with a central coordinate and semimajor/semiminor axes of $(R_{\text{proj}}/R_{200}, |\Delta v_{\text{gal}}|/\sigma_{\text{Virgo}}) = (1.2, 1.6)$ and 0.6/0.3, respectively, are the W-cloud galaxies.

Figure 9 shows the comparison of the cumulative histogram of the key quantities for the VIR, RIF, and W-cloud galaxies (the distributions of the key quantities on the PSD are presented in Appendix C). The VIR and W-cloud galaxies tend to have lower medians of SFR, sSFR, and gas fractions than the RIF galaxies. Furthermore, the W-cloud galaxies have lower medians of SFR, sSFR, $\mu_{\text{H}_2}$, and SFEs than the VIR galaxies. The W-cloud galaxies have higher $\mu_{\text{gas}}$ and $\mu_{\text{H}_2}$ medians than the RIF galaxies. Based on the KS test, the following differences are significant: (1) SFR, sSFR, and all the gas fractions between the VIR and RIF galaxies, (2) $\mu_{\text{H}_2}$ and SFE$_{\text{H}_2}$ between the VIR and W-cloud galaxies, and (3) SFR, sSFR, $\mu_{\text{H}_2}$, and SFE$_{\text{H}_2}$ between the W-cloud and RIF galaxies.

If we limit the sample to galaxies with $\text{H}_1$ or CO measurements (CO+H1 obs. sample), all the differences in (3) disappear while the difference in SFE$_{\text{H}_2}$ becomes significant. If we limit the sample to galaxies with $\text{H}_1$ or CO detections (CO+H1 det. sample), on the other hand, only the differences of SFR and sSFR between the VIR and RIF galaxies are statistically significant.

When we do not distinguish the W-cloud galaxies from the RIF galaxies, the VIR galaxies tend to have lower SFR, sSFR, gas fractions, and higher $R_{\text{H}_2}$, SFE$_{\text{gas}}$, and SFE$_{\text{H}_2}$ medians than the RIF galaxies, while no significant difference is seen in
and increasing SFE of the galaxy. Additionally, SFEHI negatively correlates with the product of SFR and clustocentric distance of the key quantities, there are positive correlations with SFR, sSFR, and cold-gas fractions of the galaxies at the largest bin of 1.0 \times \Delta R_{200}. The inclusion of the W-cloud galaxies diminishes the correlation with SFEHI, compared to field galaxies. Dispersions of the H1-related quantities are larger for the Virgo galaxies than field galaxies at fixed Δ(MS) (Figures 4 and 5 in Section 3.1 and Figures 11 and 12 in Appendix A).

4. For the dependence of the Δ(Field) values on the clustocentric distance of the key quantities, there are positive correlations with SFR, sSFR, and gas fractions with correlation coefficients of 0.3–0.5, and negative correlations with SFEgas, SFEHI, and RH1, with correlation coefficients ranging from −0.4 to −0.3. There seems to be a bend in these values between 1.5R200 and 2.0R200. The inclusion of W-cloud galaxies decreases RH1 at (1.0 − 1.5)R200. No significant dependence on the clustocentric distance is found for SFEHI (Figure 6 in Section 3.2).

5. For the dependence of the Δ(Field) values on the projected distance to the fifth nearest neighbor on the sky, there are positive correlations with SFR, sSFR, and gas fractions with a correlation coefficient of 0.3–0.4 and weak negative correlations with SFEgas and SFEHI, with a correlation coefficient of −0.3. In case of the distance to the fifth nearest neighbor on the PSD, there are correlations with SFR, sSFR, and RH1 with correlation coefficients of −0.2. There also exist positive correlations between these distances and the clustocentric distance (Figure 7 in Section 3.3 and Figures 13 and 14 in Appendix B).

6. For the dependence of the Δ(Field) values on the accretion phase of galaxies in the cluster, the SFR, sSFR, and all gas fractions in the VIR galaxies are lower than those of the RIF galaxies when the W-cloud galaxies are distinguished from the other RIF galaxies. There are positive correlations between the product of (ΔVproj/σVirgo) × (Rproj/R200) and SFR, sSFR, and all gas fractions, with correlation coefficients of −0.3–0.4 and a negative correlation with SFEHI with a correlation coefficient of −0.25. When the W-cloud galaxies are included, the correlation with RH1 becomes insignificant while the correlations with SFEgas...
Figure 9. Cumulative histograms of the stellar mass and the key quantities of galaxies in the VIR (solid line), RIF (dashed line), and W-cloud regions (dotted line). The numbers of galaxies in the VIR and RIF regions are indicated in the upper-left corner in each panel. The $p$-values of the KS test are indicated in purple in the lower-right corner.
7. Comparing three subsamples, the dependence of the key quantities on the clustocentric distance, local galaxy density, and accretion phase is basically observed for the best-effort sample and CO+H I-obs. sample but not for the CO+H I-det. sample. This is because the CO+H I-det. sample is biased to somehow similar systems, which are less affected by the environments. Information on the upper limits is necessary to understand the cold-gas properties of the Virgo galaxies.

5. Discussions

Our data show that our Virgo galaxies have lower SFR, sSFR, and gas fractions and higher SFEs for their stellar masses compared to field galaxies as previous studies reported (e.g., Rengarajan & Iyengar 1992; Fumagalli & Gavazzi 2008; Fumagalli et al. 2009; Boselli et al. 2014b), even though they are massive galaxies ($M_{\text{star}} > 10^9 M_\odot$) whose star formation activities are expected to be less affected by their environment (Peng et al. 2010). In the following sections, we discuss the effects of the inclusion of the “possible” members in our sample on the obtained results (Section 5.1) and possible quenching mechanisms in the Virgo cluster (Section 5.2).

5.1. Membership of the Virgo Cluster

In this section, we investigate the effect of the inclusion of possible members on the obtained results by removing them from the analysis. As we mentioned in Section 2.1, we use data of both the secure and possible members in the EVCC. The possible members mainly consist of the W-cloud galaxies and $R_{\text{H}}$ become significant (Figures 9 and 10 in Section 3.4 and Figure 15 in Appendix C).

Figure 10. Relationship between the accretion phase, ($|\Delta v_{\text{gal}}|/\sigma_{\text{Virgo}} \times (R_{\text{proj}}/R_{\text{200}})$), and the key quantities. The W-cloud galaxies are not included in these plots. The symbols are the same as in Figure 6.
the southern-extension galaxies. We find that the galaxies in the W cloud have lower SFR, sSFR, $\mu_{HI}$, and SFE$_{HI}$ compared to the surrounding galaxies (Section 3.4). On the other hand, the southern-extension galaxies (galaxies with higher $R_{proj}$/R$_{200}$ and higher $\Delta$gal/$\sigma_{Virgo}$ values on the PSD) tend to have a bluer SDSS color as seen in Figure 8, suggesting a higher SFR and abundant cold gas.

For the dependences on the clustocentric distance, overall trends are basically the same as what we find with the sample including both the secure and possible members. More specifically, we find the bend in the key quantities at $R_{c}$. For the dependence on the local galaxy densities, the results for $R_{sky}$ do not significantly change, while all correlations disappear for $R_{PSD}$. This difference can be attributed to the disappearance of the galaxies with high SFR, sSFR, and $\mu_{HI}$ at the sparser region on the PSD, i.e., the southern-extension galaxies. For the dependence on the accretion phase, we find that the median values of the SFR and all gas fractions are lower in the VIR galaxies than in the RIF galaxies. According to the KS test, the differences in SFR and all gas fractions are confirmed to be statistically significant. The correlations between $\left(\frac{\Delta_{\text{gal}}}{\sigma_{Virgo}}\right) \times \left(R_{proj}/R_{200}\right)$ and SFR, sSFR, and gas fractions are still statistically significant even though the correlation coefficients decrease to 0.2–0.3. Therefore, the exclusion of possible member galaxies from the EVCC does not drastically change our results obtained in Sections 3 and 4 except for the $R_{PSD}$ dependence of the key quantities. Hereafter, we discuss possible quenching mechanisms at work in the Virgo galaxies based on the obtained results with both secure and possible members in the following sections.

5.2. Quenching Mechanism in the Virgo Cluster

Our results show that the SFR, sSFR, and gas fractions of galaxies are different in samples chosen at $R_{proj} < 1.5R_{200}$ and those at $R_{proj} > 1.5R_{200}$ (Figure 6). Considering that there is a boundary between the VIR and RIF regions around $R_{proj} \sim 1.5R_{200}$, our results suggest that ram pressure and/or long-period quenching mechanisms, such as strangulation and tidal interaction with the cluster potential, play a role in affecting the cold-gas and star formation properties of the Virgo galaxies. Additionally, the correlations between the projected local densities of galaxies on the sky and the SFR, sSFR, and gas fractions suggest that galaxy–galaxy interaction also plays some role in decreasing the star formation activity in these galaxies (Figure 7). The weaker dependence of these key values on the local density on the PSD suggests that galaxy harassment is especially important for decreasing gas reservoirs and star formation activities of these galaxies (Figure 14).

Furthermore, we find that our Virgo sample tends to have a lower gas fraction and a higher SFE than the field galaxies. The field galaxies are known to follow “universal relations” between $\Delta$(MS) and $\mu_{HI}$ and between $\Delta$(MS) and SFE$_{HI}$, where galaxies with lower $\Delta$(MS) tend to have a lower $\mu_{HI}$ and SFE$_{HI}$ (e.g., Saintonge et al. 2012). However, our Virgo sample with a lower $\Delta$(MS) is found to have lower gas fractions and higher SFEs than the field galaxies. This is why our Virgo sample has higher SFEs than the field galaxies even though they are less actively forming stars. This may suggest that the gas reduction process in those galaxies with a lower $\Delta$(MS) takes place over a shorter timescale than the gas-depletion timescale by star formation, i.e., $M_{\text{gas}}$/SFR $\sim$ 3 Gyr. Considering that $\Delta$(MS) is equal to the $\Delta$(Field) of SFR, the positive correlations between the $\Delta$(Field) value of the SFR and the clustocentric distance, the distance to the fifth nearest neighbor, and $\left(\frac{\Delta_{\text{gal}}}{\sigma_{Virgo}}\right) \times \left(R_{proj}/R_{200}\right)$ indicate that the galaxies with lower $\Delta$(MS) values are located nearer to the cluster center, have smaller clustocentric velocity, and reside in denser regions.

We discuss the environmental effects on cold-gas and star formation properties in the following sections by focusing on ram pressure and tidal stripping (Section 5.2.1), galaxy harassment (Section 5.2.2), preprocessing in a group environment (Section 5.2.3), and strangulation (Section 5.2.4).

5.2.1. Ram Pressure or Tidal Stripping

Over recent decades, ram pressure stripping of cold gas in galaxies has been considered as one of the main candidate mechanisms for star formation quenching in clusters (Gunn & Gott 1972; Balsara et al. 1994; Abadi et al. 1999; Fujita & Nagashima 1999; Mori & Burkert 2000; Quilis et al. 2000; Vollmer et al. 2001; Okamoto & Nagashima 2003), and there is observational evidence that ram pressure stripping modifies atomic gas (Chung et al. 2009a) and ionized gas (e.g., Yoshida et al. 2004; Koopmann et al. 2006; Cortese et al. 2007; Ebeling et al. 2014; Poggianti et al. 2016). It is also shown that post-starburst galaxies are preferentially found at small clustocentric radii with high clustocentric velocities, suggesting that ram pressure stripping is the most plausible candidate for the physical mechanism to quench their star formation (Muzzin et al. 2014; Pacagnella et al. 2017). At the same time, ram pressure is claimed to enhance star formation activity in galaxies (Fujita & Nagashima 1999; Bekki & Couch 2003; Kronberger et al. 2008; Bekki 2014; Ruggiero & Lima Neto 2017), and there are supporting observations (e.g., Vulcani et al. 2018a; Roberts & Parker 2020; Wang et al. 2020). Additionally, ram pressure is found to induce gas funneling to the central supermassive black hole of galaxies (Poggianti et al. 2017). However, the effect of ram pressure on molecular gas in cluster galaxies is still an open question.

Comparing the VIR galaxies with the RIF galaxies without the W-cloud galaxies, we find that star formation activity and cold-gas reservoirs are significantly smaller in the former than in the latter. The atomic gas in the VIR and RPS galaxies has been known to be deficient compared to the RIF galaxies in previous studies (Jaffé et al. 2015; Wang et al. 2020), but this is the first time a similar tendency has been found in molecular gas in the Virgo galaxies on the PSD. The tendency is also confirmed by the positive correlations between $\left(\frac{\Delta_{\text{gal}}}{\sigma_{Virgo}}\right) \times \left(R_{proj}/R_{200}\right)$ and the SFR, sSFR, and gas fractions as seen in the $\sim 2.5$ cluster (Wang et al. 2018). These results suggest the importance of not only the long-period quenching processes but also the ram pressure stripping for star formation quenching because the galaxies that were affected by the ram pressure also exist in the VIR region (Jaffé et al. 2015; Wang et al. 2020).

In addition, we find that the gas fractions and SFEs of the Virgo galaxies are lower and higher than those of the field galaxies for fixed $\Delta$(MS), preferring a gas removal process whose timescale is shorter than the gas-depletion time. These results suggest that ram pressure plays an important role in the star formation quenching in the Virgo galaxies and affects not only atomic gas but also molecular gas in some cluster galaxies as previous studies claimed (e.g., Rengarajan & Iyengar 1992; Fumagalli & Gavazzi 2008; Fumagalli et al. 2009; Boselli et al. 2014b). However, there is no pure RPS galaxies with CO or
HI measurements in our sample, so our data cannot completely rule out the possibility that other long-period processes such as strangulation and tidal interaction with the cluster potential cause these changes.

In this study, SFEs are not significantly different between the VIR and RIF galaxies. Previous observational studies showed a wide variety in the spatial distribution of SFE (Fumagalli & Gavazzi 2008; Fumagalli et al. 2009; Vollmer et al. 2012; Mok et al. 2017). Vollmer et al. (2012) investigated the SFE spatial distribution of 12 Virgo spiral galaxies and found that not all but some galaxies experiencing stripping have an increased SFE\textsubscript{gas} (but not SFE\textsubscript{H\textsc{i}}) on the windward side of the galactic disks where \( R_{H\textsc{i}} \) is also high. They also showed that the extraplanar region of such galaxies tends to have reduced SFE\textsubscript{gas} (also SFE\textsubscript{H\textsc{i}} for one galaxy). Therefore, the spatial variation may hamper the difference in the integrated galactic values of SFEs as explored in this study.

On the PSD, galaxies that are affected by the tidal force of the cluster potential are predicted to be distributed similarly to the galaxies that are affected by ram pressure from the ICM according to the numerical simulations (Figures 8 and 9 of Rhee et al. 2017). In our data, when the sample is limited to "secure" members with both CO and HI measurements, the difference in \( \mu_{H\textsc{i}} \) between the VIR and RIF galaxies becomes insignificant (\( p\)-value of 0.1) whereas SFR and \( \mu_{H\textsc{i}} \) are still lower in VIR galaxies than RIF galaxies. This is rather strange, given that the ram pressure is expected to affect atomic gas more than molecular gas. This may suggest that the tidal force is more important for star formation quenching in cluster galaxies than ram pressure. Spatially resolved data of both the gaseous and stellar components of galaxies would help us to distinguish which process plays a major role in affecting star formation properties, because the ram pressure should interact only with gas whereas the tidal force is expected to affect both gas and stellar components.

5.2.2. Galaxy Harassment

The so-called density–morphology relation (i.e., Dressler 1980) suggests that the galaxy environment plays a role in changing the galaxy morphology. Galaxy harassment is one of the mechanisms leading to morphological changes due to the combined effect of tidal interactions between an infalling galaxy and the cluster potential and of the tidal interaction with close high-speed encounters with other cluster members (Moore et al. 1996, 1998). The change is claimed to depend on various parameters such as the orbit of an infalling galaxy within a galaxy cluster (Mastropietro et al. 2005; Smith et al. 2010), the surface density of the infalling galaxy (Moore et al. 1999; Chang et al. 2013), and the inclination between the orbital plane and the disk of the infalling galaxy (Villalobos et al. 2012). Haynes et al. (2007) show that the observed properties of the strongly asymmetric Virgo galaxy NGC 4254 are consistent with what are expected for galaxies in the process of galaxy harassment. However, galaxy harassment is also claimed to be only significant on specific orbits close to the cluster core and does not induce significant structural or dynamical transformation on most typical cluster orbits (Bialas et al. 2015; Smith et al. 2015).

We find a stronger dependence of the star formation activity and the cold-gas contents of galaxies on \( R_{S,\text{sky}} \) than \( R_{S,\text{PSD}} \), suggesting the importance of galaxy harassment. At the same time, we also find positive correlations between \( R_{S,\text{sky}} \) and \( R_{S,\text{PSD}} \), and the clustocentric distance, i.e., the galaxies closer to the cluster center tend to reside in the denser region. Therefore, the dependence of the star formation activity and the cold-gas contents of galaxies on the local density could be just reflecting the dependence of these properties on the clustocentric distance, and vice versa. It is difficult to conclude which are more essential correlations with our data given that the strengths of the correlations are comparable (\( r \) of \( \sim 0.3–0.5 \)). Again, spatially resolved properties of both the stellar and cold-gas components in these galaxies would provide us a clue to assess the importance of galaxy harassment for them.

5.2.3. Preprocessing in Group Environments

There are many studies suggesting that suppression of star formation in galaxies has already started before the galaxies fall deep into the cluster (preprocess; e.g., Kodama et al. 2001; Lewis et al. 2002; Gómez et al. 2003; Tanaka et al. 2005; Koyama et al. 2008; Lu et al. 2012; Rasmussen et al. 2012; Matsuki et al. 2017; Kleiner et al. 2021). More than half of the galaxies in the local universe reside in group and cluster environments (Zwicky 1938; Abell 1958; Huchra & Geller 1982; Geller & Huchra 1983; Eke et al. 2004, 2005). It is possible that the most quenched galaxies in the cluster observed today may have been preprocessed before falling into the cluster.

The star formation quenching in group galaxies has been investigated (e.g., Zabludoff & Mulchaey 1998; Balogh et al. 2004, 2009; Wilman et al. 2005; Weinmann et al. 2006; McGee et al. 2011; Rasmussen et al. 2012; Hou et al. 2013; Tal et al. 2014), and it is generally considered that galaxy harassment and tidal interactions are the most common quenching processes in the group environment (Wilman et al. 2009). X-ray-emitting hot gas has been observed in some groups (Mulchaey 2000) and the interaction with the intra-group medium (IGM) is also one of the possible quenching processes for such groups (Bekki et al. 2002; Rasmussen et al. 2008). It is also claimed that not one but several quenching processes are necessary to account for the observations (Smethurst et al. 2017; Vulcani et al. 2018b).

In Section 3.4, we find that the W-cloud galaxies have lower \( \mu_{H\textsc{i}} \) and SFE\textsubscript{H\textsc{i}} than the VIR and the RIF galaxies. Because most of the W-cloud galaxies with CO upper limits, i.e., low \( \mu_{H\textsc{i}} \) galaxies, do not have HI measurements, it is difficult to assess whether their HI gas is also deficient. However, considering the nondetections of these sources in the blind HI survey of ALFALFA, HI gas is not as abundant compared with the other Virgo galaxies that do show HI detection in ALFALFA (5\( \sigma \) sensitivity of 0.72 Jy km s\(^{-1}\), corresponding to the HI mass of 4.6 \( \times 10^7 \) \( M_\odot \) at 15.6 Mpc distance; Haynes et al. 2018).

In order to reduce a significant amount of molecular gas, either very strong gas stripping by IGM or galaxy–galaxy interactions are required. According to X-ray observations of the Virgo cluster, the hot gas does not seem to be strong at the location of the W cloud (see Figure 1), suggesting that galaxy–galaxy interactions are a more likely scenario for the CO deficiency in the W-cloud galaxies. If the W cloud is falling into the Virgo cluster, preprocessing in the group environment is one of the important paths to increase the fraction of passive galaxies in the cluster environment.

Recently, Castignani et al. (2021) claimed that star formation quenching is already at play in the filaments by investigating the CO and HI properties of 245 galaxies in the filaments...
around the Virgo cluster. They found a clear tendency from field to filament and to cluster galaxies for decreasing SFR and gas fraction. Furthermore, it is shown that $\mu_{HI}$ and $\mu_{H_2}$ decrease with increasing local galaxy density in the filament, suggesting the importance of tidal interactions.

There are few CO or HI observations toward group galaxies. Low HI gas fractions have been observed in galaxies in the Hickson Compact Groups (HCG; Hickson 1982; Verdes-Montenegro et al. 2001; Borthakur et al. 2010), although HCGs are smaller galaxy groups than the W cloud of the Virgo cluster. Distinct from the W cloud in the Virgo cluster, no significant deficiency in molecular gas has been reported in the HCG galaxies (Leon et al. 1998; Verdes-Montenegro et al. 1998; Martinez-Badenes et al. 2012). However, detailed CO mapping observations of HCG galaxies with interferometers have revealed disturbed molecular gas and star formation quenching (Alatalo et al. 2014, 2015). More samples with both CO and HI measurements are required to understand the preprocesses in group environments.

5.2.4. Strangulation

Many observational studies with a significant number of galaxy groups and clusters have shown that strangulation, not ram pressure stripping, is the dominant process for quenching star formation in galaxies (e.g., Tanaka et al. 2004; Weinmann et al. 2006; Peng et al. 2015; Paccagnella et al. 2016). Peng et al. (2015) showed that the difference in stellar metallicity between star-forming and passive galaxies is explained by long-timescale quenching with a typical timescale of 4 Gyr, which is longer than that expected for ram pressure stripping ($\sim$200 Myr, Steinhauser et al. 2016).

In our sample in the Virgo cluster, the H$_2$ gas mass in some RIF galaxies has been already reduced compared to field galaxies with matched $M_{\text{star}}$ at least at $R_{\text{proj}} \sim 3R_{200}$ (Figures 6 and 15). Thus, hot-gas, as well as cold-gas, stripping by the ICM and pre-processes in group or filament environments are expected to play some role in the reduction of cold-gas reservoirs in those galaxies. Near the cluster core, the HI gas and perhaps H$_2$ gas are likely to be stripped by ram pressure, even for the relatively massive galaxies with $M_{\text{star}} > 10^8 M_\odot$ in our sample. Galaxies whose cold gas is not completely removed by ram pressure would evolve similarly to those affected only by strangulation, but the ram pressure would somehow accelerate the quenching of star formation. In this case, the quenching timescale can be estimated by their gas-depletion timescale of $M_{\text{gas}}/\text{SFR} \sim 3$ Gyr (Figure 11), which is shorter than but still comparable to the value obtained in the previous study ($\sim$4 Gyr; Peng et al. 2015). This is consistent with previous studies, suggesting that ram pressure stripping “finishes the job” in quenching star formation in some cluster galaxies (van der Burg et al. 2018; Roberts et al. 2019).

6. Summary

We investigated atomic- and molecular-gas-related properties of massive Virgo galaxies ($M_{\text{star}} > 10^9 M_\odot$) on the PSD with the world’s largest current data set of HI and CO (194 for HI, 173 for CO, and 113 for both). For comparison, we utilize the medians of the key quantities of galaxy subsamples and the $p$-value of the KS test to assess the magnitude relationship and the statistical significance of the difference in the distribution of the key quantities, respectively. Our main results are as follows:

Virgo versus field (Section 3.1): Our sample galaxies in the Virgo cluster have lower SFR, sSFR, and gas fractions ($\mu_{HI}$, $\mu_{H_2}$, and $\mu_{\text{gas}}$) and higher SFEs ($\text{SFE}_{HI}$, $\text{SFE}_{H_2}$, and $\text{SFE}_{\text{gas}}$) compared to field galaxies with matched $M_{\text{star}}$. The Virgo galaxies basically follow the field relations between $\Delta(\text{MS})$ and the gas fractions and SFEs, but deviate to lower gas fractions and higher SFEs regimes at $\Delta(\text{MS}) < 0.0$, suggesting the importance of gas-stripping processes with a shorter timescale than the gas-depletion timescale by star formation. The Virgo galaxies with lower $\Delta(\text{MS})$ values tend to be located closer to the cluster center, have a lower clustocentric velocity, and reside in denser regions.

Clustocentric distance (Section 3.2): Overall, the galaxies closer to the cluster center have low SFR, sSFR, and gas fractions (the Spearman’s rank-order correlation coefficients $r$ of 0.3−0.5), and high SFE$_{\text{gas}}$, SFE$_{HI}$, and $R_{HI}$ ($r$ ranging from −0.4 to −0.3). The radial trends seem to change at $R_{\text{proj}} \sim 1.5R_{200}$, near the location of the boundary between the “virialized” and the “recent infallers” regions. Even in the outskirt galaxies, the medians of the gas fractions are slightly lower than those of the field galaxies. These observations suggest the importance of ram pressure gas stripping and long-period quenching processes in the Virgo cluster.

Local galaxy density (Section 3.3): The distance to the fifth nearest neighbors on the sky ($R_{5,\text{sky}}$) positively correlates with the clustocentric distance, SFR, sSFR, and gas fractions ($r$ of 0.3−0.4) and negatively correlates with SFE$_{\text{gas}}$ ($r = -0.31$) and SFE$_{HI}$ ($r = -0.28$). On the other hand, the dependence of these values on the distance to the fifth nearest neighbors on the PSD becomes weak, suggesting the importance of galaxy harassment. However, the positive correlation between $R_{5,\text{sky}}$ and the clustocentric distance indicates that the dependence of the key quantities on the local density just reflects the dependence on the clustocentric distance, and vice versa.

Accretion phase (Section 3.4): The product of $(\Delta_{\text{gal}}/\sigma_{\text{Virgo}}) \times (R_{\text{proj}}/R_{200})$ positively correlates with the SFR, sSFR, and gas fractions ($r$ of 0.3−0.4), suggesting that galaxies that were accreted onto the Virgo cluster at an earlier epoch tend to have lower star formation activity and cold-gas contents. Provided that the galaxies that were affected by ram pressure in the past can also have lower $(\Delta_{\text{gal}}/\sigma_{\text{Virgo}}) \times (R_{\text{proj}}/R_{200})$, ram pressure stripping, as well as long-period quenching processes such as strangulation and tidal interaction with the cluster potential, plays a role in star formation quenching in those galaxies.

SF quenching processes in Virgo (Section 5.2): Our results support the “hybrid” quenching scenario where multiple processes account for decreasing star formation activity in galaxies in the Virgo cluster. Combined with the recent findings by Castignani et al. (2021), our results indicate that the pre-processes in the filament and group environments, as well as strangulation, have already affected cold-gas contents in some outskirt galaxies at $R_{\text{proj}} \sim 3R_{200}$. In addition, ram pressure stripping is likely to reduce both the atomic- and molecular-gas contents and consequently decrease the star formation activity in some galaxies at $R_{\text{proj}} \sim 1.5R_{200}$. However, our data cannot rule out the possibility that the tidal interaction with the cluster...
potential, strangulation, and/or galaxy harassment causes these changes in some galaxies depending on the accretion parameters such as orbits within the cluster, velocity, and the inclinations of accreting galaxies with respect to the cluster.

However, these results are based on an incomplete and inhomogeneous data set. In order to determine definitively the effect of ram pressure on molecular-gas, CO, and HI observations of an $M_{\text{star}}$-limited complete sample of the Virgo cluster are required.

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Software: astropy (Astropy Collaboration et al. 2013), APLpy (Robitaille & Bressert 2012).

Appendix A

Comparison of Key Quantities between the Field and Virgo Galaxies

In this section, we present supplementary figures for the comparison of the key quantities between the field and the Virgo galaxies (Sections 3.1). Figure 11 shows the stellar mass dependence of the key quantities. We can see that the fraction of galaxies below the SFMS is larger for the Virgo galaxies than the field galaxies, and the Virgo galaxies tend to have lower gas fractions, a higher $R_{\text{HI}}$, and higher SFEs compared to the field galaxies. Figure 12 compares the $\Delta$ (Field) values of the field and the Virgo galaxies when limiting to those with CO or HI detections. Note that the SFR and sSFR histograms of field galaxies include all of the samples in the $z0MGS$ project regardless of the CO/HI measurements. The upper/lower limits are indicated by left-pointing/right-pointing triangles.
Figure 11. Comparison between the Virgo galaxies and field galaxies from the z0MGS (Leroy et al. 2019), xGASS (Catinella et al. 2018), and xCOLD GASS (Saintonge et al. 2017) projects: $M_{\text{star}}$ dependences of (a) SFR, (b) sSFR, (c) $M_{\text{H}_2}/M_{\text{star}}$, (d) $M_{\text{gas}}/M_{\text{star}}$, (e) $M_{\text{H}_2}/M_{\text{star}}$, (f) SFR/$M_{\text{star}}$, (g) SFR/$M_{\text{gas}}$, and (i) SFR/$M_{\text{H}_2}$. The Virgo galaxies with $M_{\text{star}}$ and SFR measurements are indicated by filled gray circles in panels (a) and (b). The Virgo galaxies with a HI detection, a HI upper limit, a CO detection, and a CO upper limit are indicated by filled orange squares, open orange squares, filled blue circles, and open blue circles, respectively. The main sequence of star-forming galaxies defined in Speagle et al. (2014) is indicated by a purple dotted line and the 0.2 dex scatter range is indicated by purple shading in the panels (a) and (b). The field relations are estimated with CO- or HI-detected galaxies, i.e., star-forming galaxies, and indicated as dashed (with nonparametric fitting) and (with third-order polynomial fitting) solid lines in panels (c)–(i). Gray-shaded regions are the errors of the nonparametric fitting and estimated by the bootstrap method with a 95% confidence interval. The contours indicate field galaxies used to derive the field relations. The lower/upper limits of field galaxies are indicated by open triangles/inverted triangles. For the $R_{\text{HI}}$ panel, the field galaxies with HI and CO upper limits are indicated by X marks.
Figure 12. Same as Figure 4 but the galaxies with CO/H I detections and the galaxies with CO/H I upper limits are presented separately. The upper limits for the field and the Virgo galaxies are indicated as open gray and blue triangles, respectively. The values of the y-axis for the upper limits are assigned randomly within certain ranges.
Appendix B
Local Density Dependence of the Key Quantities

In this section, we present supplementary figures for the dependence of the key quantities on the local galaxy density (Section 3.3). Figure 13 shows the relations between $R_{5, \text{sky}}$ and $R_{5, \text{PSD}}$ with the clustocentric distance. There are moderate and weak correlations between $R_{5, \text{sky}}$ and $R_{5, \text{PSD}}$ with the clustocentric distance, respectively. Figure 14 shows the relations between $R_{5, \text{PSD}}$ and the key quantities. As mentioned in Section 3.3, overall, there is a weaker dependence of the key quantities on $R_{5, \text{PSD}}$ than on $R_{5, \text{sky}}$. According to the $p$-values, the correlations between $R_{5, \text{PSD}}$ and SFR, sSFR, and $\mu_{H_1}$ are statistically significant.

Figure 13. Relationship between the clustocentric distance and the distance to the fifth nearest galaxy on the sky $R_{5, \text{sky}}$ (left) and on the PSD $R_{5, \text{PSD}}$ (right) as measures of the local galaxy density. The individual data are indicated by gray filled circles and the median values for each radius bin are indicated by black filled circles. The error bars indicate the first and third quartiles. The correlation coefficient is indicated in the lower-left corner in purple.
Appendix C

Key Quantities on the PSD

In this section, we present supplementary figures of the distributions of the key quantities on the PSD (Sections 3.4 and 5.1). Figures 15 and 16 are, respectively, the PSDs of the secure+possible and only secure members, color-coded according to the key quantities without the stellar mass dependences of field galaxies $[\Delta({\rm Field})]$. The zero value indicates the values for the field galaxies and the bluish/reddish colors indicate that the values are higher/lower than the field galaxies.

Figure 14. Same as Figure 7, but for $R_{5,PSD}$.
Figure 15. Stellar mass and the key quantity [$\Delta$][Field] varieties on the PSD. The colors of the symbols indicate the values of the key quantities. The zero of each key quantity indicates the values of the field galaxies except for the stellar mass (white), i.e., the bluish and reddish colors indicate values that are higher and lower than those of field galaxies, respectively.
Figure 16. Stellar mass and key quantity [$\Delta$(Field)] varieties on the PSD without the possible EVCC members. The colors of the symbols indicate the values of the key quantities. The zero of each key quantity indicates the values of the field galaxies except for the stellar mass (white), i.e., the bluish and reddish colors indicate values that are higher and lower than those of field galaxies, respectively.

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