Star-forming Dwarf Galaxies in Filamentary Structures around the Virgo Cluster:
Probing Chemical Pre-processing in Filament Environments

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Abstract

It has been proposed that the filament environment is closely connected to the pre-processing of galaxies, where their properties may have been changed by environmental effects in the filament before they fell into the galaxy cluster. We present the chemical properties of star-forming dwarf galaxies (SFDGs) in five filamentary structures (Virgo III, Leo Minor, Leo II A, Leo II B, and Canes Venatici) around the Virgo cluster using the Sloan Digital Sky Survey optical spectroscopic data and Galaxy Evolution Explorer ultraviolet photometric data. We investigate the relationship between stellar mass, gas-phase metallicity, and specific star formation rate (sSFR) of the SFDGs in the Virgo filaments in comparison to those in the Virgo cluster and field. We find that, at a given stellar mass, SFDGs in the Virgo filaments show lower metallicity and higher sSFR than those in the Virgo cluster on average. We observe that SFDGs in the Virgo III filament show enhanced metallicities and suppressed star formation activities comparable to those in the Virgo cluster, whereas SFDGs in the other four filaments exhibit similar properties to the field counterparts. Moreover, about half of the galaxies in the Virgo III filament are found to be morphologically transitional dwarf galaxies that are supposed to be on the way to transforming into quiescent dwarf early-type galaxies. Based on the analysis of the galaxy perturbation parameter, we propose that the local environment represented by the galaxy interactions might be responsible for the contrasting features in chemical pre-processing found in the Virgo filaments.

Unified Astronomy Thesaurus concepts: Galaxy abundances (574); Star formation (1569); Galaxy clusters (584); Galaxy formation (595); Galaxy evolution (594); Large-scale structure of the universe (902)

1. Introduction

The large-scale structure of the Universe is characterized by a web-like network composed of filaments that intersect at nodes wherein clusters of galaxies are found (Bond et al. 1996). Filaments are the most dominant structures in the distribution of galaxies, extending over scales up to tens of megaparsecs. Moreover, a significant fraction of the mass in the Universe is concentrated in filaments (Aragón-Calvo et al. 2010). The hierarchical models of structure formation predict that galaxy clusters grow by the continuous accretion of galaxies through filaments (Ebeling et al. 2004). The role of the filament on the properties and evolution of galaxies has been investigated by numerous studies regarding the subject of pre-processing (Fujita 2004). In particular, there is a growing body of observational results on star formation quenching of galaxies in the filament environments (Martínez et al. 2016; Kuutma et al. 2017; Castignani et al. 2021). The changes of galaxy properties as a function of the distance from the filament spine or node have also been extensively investigated (Alpaslan et al. 2016; Martínez et al. 2016; Chen et al. 2017; Kuutma et al. 2017; Malavasi et al. 2017; Kraljic et al. 2018; Laigle et al. 2018; Mahajan et al. 2018; Luber et al. 2019; Sarron et al. 2019; Bonjean et al. 2020; Lee et al. 2021). On the other hand, several studies have also reported that the filament environment connected with the cluster is responsible for enhanced star formation activity and an increased fraction of star-forming galaxies in the filaments (Porter & Raychaudhury 2007; Fadda et al. 2008; Biviano et al. 2011; Coppi et al. 2012; Darvish et al. 2014). These observational results provide evidence that the properties of galaxies may have been changed in the filaments via several environmental effects before they fell into galaxy clusters.

From the perspective of the provision of invaluable information on galaxy evolution, gas-phase metallicity could be a unique observable parameter for probing the chemical evolution of galaxies. As galaxies evolve, metals produced by nucleosynthesis are released into the surrounding interstellar medium during the later evolutionary stages of stars. As the cycle of star formation recurs, the metals in the interstellar medium of the galaxy become steadily enriched. Thus, the metallicity traces a fossil record of the star formation history. Several studies have also attempted to identify the relationship between the chemical properties of galaxies and their surrounding environments (e.g., Skillman et al. 1996; Pilyugin et al. 2002; Hughes et al. 2013). Skillman et al. (1996) and Pilyugin et al. (2002) found that spiral galaxies near the core of the Virgo cluster have higher oxygen abundances than those in the field environment. However, Hughes et al. (2013) suggested that internal evolutionary processes, rather than environmental effects, play a key role in the chemical evolution of cluster galaxies. While the role of the environment in shaping the chemical evolution of galaxies remains a controversial issue, a sophisticated approach that can provide accurate understandings of the impact of the environment is required.

To date, observational studies of filament galaxies using gas-phase metallicity have focused on massive (>10⁹ M☉) bright galaxies mainly because of their affluence of observations (e.g., Darvish et al. 2015). However, low-mass galaxies are more
vulnerable to even weak external influences because their gravitational potential wells are more shallow than that of massive galaxies. Thus, they are ideal objects for probing various processes that alter the properties and evolution of galaxies in filament environments.

The Virgo cluster is the nearest rich cluster from the Milky Way at a distance of \(~17\text{ Mpc}\) (Mei et al. 2007; Boselli et al. 2014). Moreover, since the Virgo cluster is considered to be a dynamically young cluster (Aguerri et al. 2005), a connection of the galaxy distribution of the cluster to the nearby filament structures was expected (Tully 1982). Recently, Kim et al. (2016) defined the filament structures that are physically connected to the Virgo cluster. These Virgo filaments are mostly composed of faint dwarf galaxies (\(M_B > -19\text{ mag}\); \(~88\%\) of the total sample) and exhibit a range of characteristics (e.g., galaxy number density, length, and thickness of the filaments; Lee et al. 2021). Most recently, two studies have quantified the properties of galaxies in the Virgo filaments in terms of their colors, star formation rate, and gas content with respect to the vertical distance from the filament spine and local galaxy density (Castignani et al. 2021; Lee et al. 2021). As part of our study of the galaxies in the Virgo filaments, we explore the effects of the filament environment on the chemical properties of star-forming dwarf galaxies (SFDGs) in the Virgo filaments using the Sloan Digital Sky Survey (SDSS) optical spectroscopic data and Galaxy Evolution Explorer (GALEX) ultraviolet (UV) photometric data.

This paper is structured as follows. In Section 2 we describe the selection of the SFDGs in the Virgo filaments, Virgo cluster, and field. Estimations of the basic parameters of the SFDGs are also presented. In Section 3 we show the results of the gas-phase metallicity and SFR of the SFDGs in the Virgo filaments in comparison with those in the Virgo cluster and field. We also present a discussion of physical processes in filaments in terms of the chemical pre-processing. Finally, we summarize our results in Section 4. Throughout this paper, we assume a flat \(\Lambda\) cold dark matter cosmology with \(H_0 = 100h\text{ km s}^{-1}\text{ Mpc}^{-1}\), \(h = 0.7\), \(\Omega_m = 0.3\), and \(\Omega_{\Lambda} = 0.7\) (Komatsu et al. 2011).

## 2. Data and Analysis

### 2.1. Selection of Dwarf Galaxies in Different Environments

Based on the SDSS Data Release (DR) 7 and HyperLeda database, Kim et al. (2016) identified seven filaments around the Virgo cluster. The majority of galaxies associated with the Virgo filaments are low-mass dwarf galaxies (>10\(^7\) \(M_{\odot}\); ~87% of the total sample; Lee et al. 2021). We only extracted 571 galaxies in the five filaments (i.e., Virgo III, Leo Minor, Leo II A, Leo II B, and Canes Venatici) that are known to be dynamically connected to the Virgo cluster (see Kim et al. 2016 for details).

For an adequate comparison with galaxies in a cluster environment, we used galaxies in the Extended Virgo Cluster Catalog (EVCC; Kim et al. 2014). The EVCC contains a comprehensive galaxy sample (1589 galaxies) in a wide area of 725 deg\(^2\) or 60.1 Mpc\(^2\) reaching out to the outskirts of the Virgo cluster (i.e., 3.5 times the virial radius of the Virgo cluster).

We selected field galaxies at \(z < 0.01\) by assuming a cylinder volume constructed using the SDSS data. The circle radius of a cylinder volume was adopted to be 350 kpc, which corresponds to a virial radius of an early-type galaxy with \(M_r = -20.5\text{ mag}\) (Park et al. 2008). We adopted a radial velocity depth of \(\pm 700\text{ kms}^{-1}\), which is the 1\(\sigma\) of velocity dispersion of the Virgo cluster (Binggeli et al. 1985). If only one galaxy was located in the cylinder volume, we defined this galaxy as a field galaxy. We secured 505 field galaxies. To obtain insights regarding the environment of the selected field galaxies, we computed their three-dimensional density contrast (i.e., overdensity), \(\delta_{\text{1,1000}}\) within a cylinder of a 1 h\(^{-1}\) Mpc radius and 1000 kms\(^{-1}\) half-length, which is defined as follows (Gavazzi et al. 2010):

\[
\delta_{\text{1,1000}} = \frac{\rho - \langle \rho \rangle}{\langle \rho \rangle},
\]

where \(\rho\) is the local galaxy number density, and \(\langle \rho \rangle\) is the mean galaxy number density measured in the Coma/A1367 super-cluster region (i.e., 0.05 galaxy (h\(^{-1}\) Mpc\(^{-3}\)). Most of the field galaxies have values of \(\delta_{\text{1,1000}} < 0\), indicating that the selected field galaxies are located in ultra-low-density environments (Gavazzi et al. 2010).

Finally, we selected dwarf galaxies in three different environments based on the morphological classification as described by Sandage & Binggeli (1984). The morphological classification of the EVCC was carried out by careful visual inspection of SDSS images (see Kim et al. 2014 for details). The selected 1325 dwarf galaxies in the Virgo cluster consist of early-type dwarf galaxies, high surface brightness irregular galaxies, and low surface brightness irregular galaxies. We also selected dwarf galaxy samples in the Virgo filaments (361 galaxies) and field (336 galaxies) by conducting visual inspections of SDSS images, according to the scheme of the EVCC. Our selected dwarf galaxy samples are in the magnitude range of ~19 < \(M_r\) < ~12.

### 2.2. Measurement of Emission Lines

We extracted optical spectra of our 2022 dwarf galaxies in different environments from the SDSS DR12. In the SDSS, the spectra were observed through 3\(^{rd}\) fibers, giving a wavelength coverage of 3800 Å to 9200 Å at a spectral resolution of 1500–2500 (Alam et al. 2015). To obtain emission line fluxes, we modeled the underlying stellar continuum of the SDSS spectrum for each galaxy by using the STARLIGHT stellar population synthesis code (Cid Fernandes et al. 2004, 2005; Mateus et al. 2006). We fitted the observed spectrum with a combination of 150 multiple simple stellar populations (six metallicities and 25 ages) taken from the evolutionary synthetic models of Bruzual & Charlot (2003). After subtracting the stellar continuum, we measured fluxes of emission lines with Gaussian profiles using the MPFIT IDL routine (Markwardt 2009). For correction of internal extinction to the measured emission line fluxes, we used the theoretical Balmer ratios of \(H\alpha/H\beta = 2.86\) and \(H\gamma/H\beta = 0.47\) for Case B emissivity with a temperature of 10,000 K and an electron density of 100 cm\(^{-3}\) (Osterbrock & Ferland 2006). We only selected galaxies with signal-to-noise ratios higher than 5 for the \([\text{OIII}]\lambda5007, H\gamma, H\beta, \text{H}\alpha, [\text{N II}]\lambda6584, \text{and [S II]}\lambda\lambda6717,6731\) emission lines.

### 2.3. Selection of Star-forming Dwarf Galaxies

We identified SFDGs using the Baldwin–Phillips–Terlevich (BPT) diagram constructed from the measured emission line ratios \([\text{OIII}]\lambda5007/H\beta\) and \([\text{N II}]\lambda6584/H\alpha\). The BPT is used to classify galaxies according to the excitation mechanism of their emission lines (i.e., either photoionization by young massive stars within H II regions or photoionization by non-thermal radiation from the active galactic nucleus (AGN;
with overall blue colors and are dominated by single or multiple H$_\text{II}$ regions. Some L-SFDGs exhibit elliptical shapes in the outer part, but they show overall blue colors and irregular structures at their centers. In Figure 3 we present examples of SDSS color images of E-SFDGs and L-SFDGs in the Virgo filaments, Virgo cluster, and field.

The morphological characteristics of E-SFDGs and L-SFDGs are also consistent with their optical spectra (see the bottom panels of Figure 3). The L-SFDGs show strong narrow emission lines, indicative of intense star formation. Emission lines such as H$_\alpha$, H$_\beta$, and [O III] are predominant compared to the continuum in optical spectra (see the bottom left three panels of Figure 3). However, E-SFDGs have relatively weak emission lines and are less dominant than the continuum level (see the bottom right three panels of Figure 3). However, optical spectra reveal that E-SFDGs are objects with hints of recent or ongoing star formation at their central regions.

2.5. Gas-phase Metallicity, Star Formation Rate, and Stellar Mass

The gas-phase metallicity of a galaxy is usually specified by the oxygen abundance, the most abundant metal within its interstellar medium. We estimated the gas-phase oxygen metallicity using the following empirical relationship derived by Denicoló et al. (2002):

$$12 + \log(O/H) = 9.12 + N2 \times 0.73,$$

where $N2$ is the metallicity indicator of $N2 = \log([N\ II]/\lambda6584/\ H\ alpha)$ (Denicoló et al. 2002). The total UV flux from the GALEX mission reflects the overall star formation of a galaxy. GALEX provides UV sky surveys with wide area coverage and deep sensitivity in two UV bands: far-UV (FUV; 1350–1750 Å) and near-UV (NUV; 1750–2750 Å). The UV fluxes of the SFDGs were taken from the GALEX archive. We derived the NUV star formation rates (SFRs) of the SFDGs from the relation given by Kennicutt (1998) based on the NUV luminosity ($L_{\text{NUV}}$):

$$\text{SFR}_{\text{NUV}}(M_\odot/yr^{-1}) = 1.4 \times 10^{-28} L_{\text{NUV}}(\text{erg s}^{-1}\text{Hz}^{-1}).$$

The stellar masses of the SFDGs were derived using the relation between the SDSS $g-i$ color and the stellar mass-to-light ratio based on the $i$-band luminosity ($L_i$; Bell et al. 2003) assuming the initial mass function of Kroupa et al. (1993):

$$\log(M_*/M_\odot) = -0.152 + 0.518(g - i) + \log(L_i/L_\odot).$$

For the SFR and stellar mass calculations, based on the reddening law of Cardelli et al. (1989), we corrected galactic extinctions for the magnitudes using the E($B-V$) value from the NASA/IPAC Extragalactic Database. The distances of the SFDGs in the Virgo filaments and field were estimated using their radial velocities. In the case of the Virgo cluster, we assumed the distances of all SFDGs to be 17 Mpc by adopting the typical distance of the main body of the Virgo cluster (Boselli et al. 2014).

3. Results and Discussion

3.1. O/H versus Stellar Mass and Specific Star Formation Rate versus Stellar Mass Distributions

In Figures 4(a) and (c), we present the distributions of O/H versus stellar mass and sSFR versus stellar mass for SFDGs in
the Virgo filaments (filled red circles) and Virgo cluster (filled green circles). The error-weighted best linear fit to the SFDGs in the Virgo cluster is shown as the solid green line: 

$$12 + \log(O/H) = 0.27 \log(M_* / M_\odot) + 6.10$$

for O/H versus stellar mass and

$$\log(sSFR) = -0.55 \log(M_* / M_\odot) - 5.62$$

for sSFR versus stellar mass. The O/H and sSFR residuals from the linear fit to the Virgo cluster are also presented in Figures 4(b) and (d). In these plots, the distributions of the SFDGs in the Virgo cluster are shown as contours. Dashed lines are 1σ deviations from the mean of the SFDGs in the Virgo cluster. Insets represent residuals and errors of the SFDGs at different mass bins. Green and red histograms
represent residual distributions of the SFDGs in the Virgo filaments and Virgo cluster, respectively. While there is obvious scatter, the SFDGs in the Virgo filaments and Virgo cluster appear to show different distributions in Figure 4. The SFDGs in the Virgo filaments deviate toward a lower O/H than those in the Virgo cluster at a given stellar mass. However, SFDGs in the Virgo filaments show a higher mean sSFR at a given stellar mass compared to their Virgo cluster counterparts, which is consistent with the well-known anti-correlation between O/H and sSFR (Lara-López et al. 2010; Mannucci et al. 2010; Hunt et al. 2012; Yates et al. 2012). The Kolmogorov–Smirnov (K-S) tests for O/H and sSFR residuals from the linear fit to the Virgo cluster yielded probabilities of $P \approx 0.007$ and $P \approx 0$, respectively. These tests indicate that the differences in O/H and sSFR distributions between the SFDGs in the Virgo filaments and Virgo cluster are statistically significant.

In Figure 5 we present the distributions of O/H versus stellar mass and sSFR versus stellar mass for SFDGs in the Virgo filaments (filled red circles) and field (open black circles). For comparison, the best linear fit to the SFDGs in the Virgo cluster is shown as the solid green line. The O/H and sSFR residuals from the linear fit to the Virgo cluster are also presented in Figures 5(b) and (d). In these plots, the distributions of the SFDGs in the field are shown as contours. Dashed lines are $1\sigma$ deviations from the mean of the SFDGs in the Virgo cluster. Insets represent residuals and errors of the SFDGs at different mass bins. Black and red histograms represent residual distributions of the SFDGs in the Virgo cluster and Virgo filaments, respectively.

As shown in Figure 5, the SFDGs in the Virgo filaments tend to share similar distributions with those in the field without showing a significant systematic difference. The K-S tests for O/H and sSFR residual distributions between the SFDGs in the Virgo filaments and field yielded probabilities of $P \approx 0.81$ and $P \approx 0.78$, respectively. This indicates that the O/H and sSFR distributions between the SFDGs in the Virgo filaments and field are not statistically different.

### 3.2. Effects of the Environment

There has been a debate about the role of environmental effects on the metallicity and star formation activity in star-forming galaxies (Skillman et al. 1996; Hughes et al. 2013). An environmental process related to the hot intergalactic medium, such as ram pressure stripping, is vital for chemical enrichment and star formation regulation in galaxy clusters (Gunn & Gott 1972). If the ram pressure exceeds the gravitational restoring force of a galaxy, a significant fraction of the interstellar medium
in the outskirts of the galaxy would be removed. This process can cause a deficit in the pristine gas reservoir of the galaxy.

Ram pressure stripping is primarily dominant in the central region of a cluster (e.g., inside of one virial radius of the cluster; Tonnesen et al. 2007). In the case of low-mass star-forming galaxies that reside in the cluster core, ram pressure stripping can efficiently remove the H\textsc{i} interstellar gas, which gives rise to chemical enrichment and the suppression of star formation (e.g., Petropoulou et al. 2012). However, the ram pressure in the outskirts of the clusters outside of one virial radius is expected to be \( \sim 100 \) times lower than that in the core of the cluster (Tecce et al. 2011). In the case of the Virgo cluster, the majority (\( \sim 78\% ; 187/241 \)) of the SFDGs reside beyond the region of one virial radius from the cluster center (\( R_{\text{vir}} = 5.21 \) or 1.55 Mpc; Ferrarese et al. 2012; see also the dashed circle in Figure 2), indicating that most SFDGs in the Virgo cluster would be less sensitive to the ram pressure stripping effect.

By dividing SFDGs in the Virgo cluster into two subsamples located inside (filled yellow circles) and outside (filled blue circles) of one virial radius of the Virgo cluster, we present their O/H versus stellar mass and sSFR versus stellar mass distributions in Figure 6. In Figures 6(a) and (c), the error-weighted best linear fit to the SFDGs located outside of one virial radius of the Virgo cluster is shown as the solid blue line. The O/H and sSFR residuals from this linear fit are also presented in Figures 6(b) and (d). If SFDGs in the cluster core suffer more gas stripping by ram pressure than their counterparts in the cluster outskirts, the distributions of O/H and sSFR between the two subsamples are expected to differ. However, as shown in Figure 6, the two subsamples show no distinct different distributions in the two panels. The K-S tests for O/H and sSFR residuals between two subsamples yielded probabilities of \( P \sim 0.97 \) and \( P \sim 0.69 \), respectively. This indicates that the O/H and sSFR distributions between SFDGs located inside and outside of one virial radius of the Virgo cluster are not statistically different. We suggest that ram pressure is not the primary driver of the metallicity enhancement and star formation suppression in SFDGs of the Virgo cluster.

The interaction between galaxies is considered one of the typical environmental processes. The tidal forces in galaxy interactions can remove a large fraction of gas from galaxies, which leads to a subsequent decrease in star formation activity and the enhancement of metallicity (Barnes & Hernquist 1991; Mihos & Hernquist 1994, 1996; Di Matteo et al. 2007; Ellison et al. 2009). Ellison et al. (2009) have shown that the gas-phase metallicity is mainly affected by the local environment in which galaxies with a close companion galaxy in locally higher-density environments show higher O/H than those with no near neighbors.
To quantify the effectiveness of interactions between galaxies, we calculated the perturbation parameter $f$ of the SFDGs in the Virgo filaments and Virgo cluster. The $f$ value is defined by Varela et al. (2004) as

$$f = \log\left(\frac{F_{\text{ext}}}{F_{\text{int}}}\right) = 3\log\left(\frac{R}{D_p}\right) + 0.4(m_G - m_p),$$

(5)

where $F_{\text{ext}}$ indicates the tidal force exerted by the primary galaxy and $F_{\text{int}}$ is the internal force in the outskirts of the secondary galaxy, $R$ is the size of the secondary galaxy, $D_p$ is the projected distance between the primary and the secondary, and $m_G$ and $m_p$ are the apparent magnitudes of the secondary and the primary, respectively. The $f$ value signifies the ratio of the internal force and external tidal force acting on the galaxy by a possible perturber. For the $f$ value calculation of each SFDG, we considered all SDSS galaxies with a relative velocity of less than 500 km s$^{-1}$ within its environment. The galaxy with the highest $f$ value is chosen to be the perturber that exerts the most significant tidal force on the SFDG. We defined galaxies with $f > -4.5$ as those under the influence of tidal perturbation (Varela et al. 2004). The $f$ value can be considered as a proxy of the local environment because this value depends on the distance and luminosity ratio of two galaxies.

Figure 6. Panels (a) and (c): O/H vs. stellar mass and sSFR vs. stellar mass distributions of the two SFDG subsamples located inside (filled yellow circles) and outside (filled blue circles) of one virial radius of the Virgo cluster. The solid blue line denotes the best linear fit to the SFDGs located outside of one virial radius of the Virgo cluster. Panels (b) and (d): Residual distributions of the O/H and sSFR from the linear fit to the SFDGs located outside of one virial radius of the Virgo cluster. Dashed lines are 1σ deviations from the mean. Insets represent residuals of two subsamples. The error bars are uncertainties obtained from 10,000 bootstrap resampling. Histograms represent the residual distributions of the two subsamples.

Figure 7. Distributions of $f$ values of the SFDGs in the Virgo filaments (red histogram) and Virgo cluster (light green histogram). The vertical red and black lines denote the median $f$ values of the SFDGs in the Virgo filaments and Virgo cluster, respectively. The error bars are uncertainties obtained from 10,000 bootstrap resampling. The median and error of $f$ values of the SFDGs in the Virgo filaments and Virgo cluster are also given.

Figure 7 shows the $f$ value distributions of the SFDGs in the Virgo filaments (red histogram) and Virgo cluster (light green histogram). The vertical red and black lines represent the
3.3. Environmental Disparity between Virgo Filaments

We examined the properties of the SFDGs in individual Virgo filament by comparing them with those in the Virgo cluster and field. Figure 8 shows the O/H (upper panels) and sSFR (lower panels) residuals from the linear fit to the Virgo cluster for each Virgo filament. Symbols are the same as those in Figures 4 and 5. Although there are small number statistics and scatter, the residual O/H distribution of the Virgo III filament appears different from the distributions of the other four filaments. While SFDGs in the Virgo III filament are located around the mean of the Virgo cluster (solid green line), the SFDGs in the other filaments deviate slightly (e.g., Leo Minor and Leo II A) or distinctly (Leo II B and Canes Venatici) toward the negative residuals. Moreover, the SFDGs in the Virgo III filament show a similar distribution to that of the Virgo cluster (green contours), whereas the SFDGs in the other filaments exhibit rather field-like distributions (dashed contours). The difference between the Virgo III and other filaments is more significant in the sSFR residual distributions. About half of all the SFDGs in the Virgo III filament have negative residuals (i.e., lower sSFRs than the mean of the Virgo cluster) that overlap with the distribution of the Virgo cluster. However, most SFDGs in the other filaments show systematically positive residuals (i.e., higher sSFRs than the mean of the Virgo cluster), consistent with the distribution of field SFDGs. The similarity of O/H and sSFR of the SFDGs in the Virgo III filament with those in the Virgo cluster implies that the properties of the SFDGs in the Virgo III filament may have already been changed before they fell into the Virgo cluster (i.e., pre-processing).

Several environmental effects are suggested as possible mechanisms for the galaxy pre-processing in filaments. Galaxies moving along the filaments can accrete cold gas from the intrafilament medium that replenishes some HI gas into filament galaxies (Kereš et al. 2005; Sancisi et al. 2008; Darvish et al. 2015; Kleiner et al. 2017). Darvish et al. (2015) found that star-forming galaxies in filaments at $z \sim 0.5$ have higher metallicity than those in the field on average, probably owing to the inflow of the pre-enriched intrafilamentary gas into filament galaxies. They also showed that the electron densities of the filament galaxies are significantly lower than those of the field counterparts, which might be due to a longer star formation timescale by gas accretion for filament star-forming galaxies.

We calculated the electron densities of the SFDGs in the Virgo III filament in comparison to the field SFDGs using the [S II] $\lambda 6717/\lambda 6731$ ratios (Osterbrock & Ferland 2006). The median [S II] $\lambda 6717/\lambda 6731$ ratios with $1\sigma$ errors of the SFDGs in the Virgo III filament and field are $1.33 \pm 0.13$ and $1.32 \pm 0.17$, respectively. The K-S test for electron density distributions yielded a probability of $P \approx 0.55$, indicating no significant difference in the electron densities of the SFDGs between the Virgo III filament and field. Moreover, it is worth noting that gas accretion is only enabled for the massive galaxies in filaments (e.g., $>10^{10.5} M_{\odot}$; Kleiner et al. 2017) due to their high gravitational potentials that are sufficient to pull cold gas from the intrafilament medium. Consequently, we suggest that the inflow of pre-enriched intrafilamentary gas is not responsible for the observed chemical enrichment of the SFDGs, which are in the mass range of $<10^{10.5} M_{\odot}$ in the Virgo III filament.

We calculated the perturbation parameter $f$ values of the SFDGs in each Virgo filament, which trace the effectiveness of
Figure 9. Distributions of $f$ values of the SFDGs in each filament (red histogram) and Virgo cluster (light green histogram). The vertical red and black lines denote the median $f$ values of the SFDGs in the Virgo filaments and Virgo cluster, respectively. The error bars are uncertainties obtained from 10,000 bootstrap resampling. The median and error of $f$ values of the SFDGs in each filament are also given.

suggests that the SFDGs in the Virgo III filament are in a different local environment from those in the other filaments, but are rather comparable to the Virgo cluster, where tidal interactions between galaxies are more frequent.

3.4. Transitional Dwarf Galaxies

In the context of the morphologies of galaxies related to the physical conditions of the environment in which galaxies are located (Dressler 1980; Binggeli et al. 1987), we examined the morphological properties of the SFDGs in the Virgo filaments. The L-SFDGs with overall irregular shapes and blue colors are the dominant population (82%, 172/210) in the Virgo filaments. However, it is interesting to note that a fraction of E-SFDGs (18%, 38/210), which are characterized by overall elliptical shapes with red colors but bluer colors at their centers, are also found (see Section 2.4 and Figure 3).

In Figure 10 we present the residual O/H and sSFR distributions of E-SFDGs (small yellow circles) and all SFDGs (large red circles) in the Virgo III filament and the other four filaments by comparing them with E-SFDGs (blue stars) and all SFDGs (green contours) in the Virgo cluster. Histograms also reflect the O/H and sSFR distributions of different subsamples of the SFDGs; E-SFDGs in the Virgo filaments (brown), E-SFDGs in the Virgo cluster (blue), all the SFDGs in the Virgo filaments (red), and all the SFDGs in the Virgo cluster (green). Overall, the histograms representing E-SFDGs show skewed distributions toward the higher metallicities and lower sSFRs compared to those of all the SFDGs regardless of the environment. This result implies that the E-SFDGs are chemically evolved objects with low star formation activities.

One interesting feature is that both the distributions of the O/H and sSFR of E-SFDGs in the Virgo III filament are very similar to those of the Virgo cluster. The median values and bootstrap resampling errors of $[\Delta \log(O/H), \Delta \log(sSFR)]$ are $[0.13 \pm 0.03, -0.18 \pm 0.07]$ and $[0.12 \pm 0.02, -0.30 \pm 0.03]$ for E-SFDGs in the Virgo III filament and Virgo cluster, respectively. However, E-SFDGs in the other four filaments show a hint of a slightly different distributions from those in the Virgo cluster. The E-SFDGs in the other filaments appear to be more metal poor on average and have higher sSFR than their counterparts in the Virgo cluster. The median values and bootstrap resampling errors of $[\Delta \log(O/H), \Delta \log(sSFR)]$ are $[0.05 \pm 0.04, 0.01 \pm 0.10]$ for E-SFDGs in the four filaments. Moreover, it is worth noting that a substantial fraction of the SFDGs (≃45%, 18/40) are E-SFDGs in the Virgo III filament, while only a small fraction of E-SFDGs are found in the other filaments (≃16% for Leo II A, ≃11% for Leo II B, and ≃0% for Leo Minor and Canes Venatici).

In terms of the characteristics of their morphologies, the E-SFDGs are considered transitional dwarf galaxies—those on the way to transforming into red, quiescent dwarf early-type galaxies (dEs) from late-type progenitors—dubbed blue-cored dEs (dE(bc)s; e.g., Lisker et al. 2006). It has been known that dE(bc)s are mostly found in the outskirts of clusters and moderately dense groups (De Rijcke et al. 2003; Cellone & Buzzoni 2005; Lisker et al. 2006; Tully & Trentnhom 2008; De Rijcke et al. 2013; Pak et al. 2014; Chung et al. 2019).

Ram pressure stripping and galaxy harassment have been proposed as the two most discussed formation processes of dE(bc)s in a cluster (Moore et al. 1998; Mastropietro et al. 2005; Lisker et al. 2006). However, ram pressure stripping would be nearly absent in a filament environment in which no
observational evidence for the detection of a hot intrafilamentary medium with high density has been reported (but see Benítez-Llambay et al. 2013 for a simulation of cosmic web stripping). Galaxy harassment occurs in the central region of a cluster via multiple gravitational interactions with massive member galaxies. However, this process could also be less relevant in the Virgo filaments, where the galaxy number density is relatively low, and most of the galaxies are faint low-mass dwarf galaxies.

In the case of a group environment with a relatively low-velocity dispersion, gravitational tidal interactions are suggested as the most probable mechanism for the formation of dE(bc)s (see Pak et al. 2014 for details of the Ursa Major group, where direct evidence of galaxy interaction is reported). Regarding the interaction probability, it is noteworthy that the median $f$ value of early-type galaxies in the Ursa Major group ($-3.22$; Pak et al. 2014) is comparable to that of the E-SFDGs in the Virgo III filament ($-3.78$), but is higher than E-SFDGs in the other filaments (e.g., $-4.54$ for Leo II A and $-4.49$ for Leo II B filaments). Furthermore, the Virgo filaments are known to contain a large number of groups in their structures (Castignani et al. 2021; Lee et al. 2021). Consequently, we suggest that the local environment of the Virgo III filament may be more similar to that of the group compared to the other Virgo filaments, where a high frequency of transitional dwarf galaxies can emerge through frequent galaxy interactions.

Another possible mechanism for the formation of dE(bc)s is the merger between low-mass galaxies with available gas reservoirs (e.g., Bekki 2008; Watts & Bekki 2016). The mergers between galaxies lead to the triggering of starburst in the central region through the infall of gas, which eventually forms a galaxy morphologically similar to the dE(bc)s. The observed properties of the internal kinematics of dE(bc)s in the Virgo cluster is evidence that a merging event is a formation channel for at least some of the transitional dwarf galaxies (Chung et al. 2019). In contrast to the cluster environment, galaxy mergers are more frequent in low-density environments such as a galaxy group with low relative velocities between galaxies (Binney & Tremaine 1987). Therefore, some of E-SFDGs in the Virgo filaments with a local environment comparable to that of a group could be formed by this event. In this respect, studies of the internal kinematics of large samples of E-SFDGs in the Virgo filaments are highly expected.

### 4. Summary and Conclusions

In this paper, we presented the chemical properties and star formation activity of the SFDGs in five filamentary structures physically connected to the Virgo cluster by comparing them...
with those in the Virgo cluster and field. Our main results are as follows:

1. We selected 210, 241, and 305 SFDGs in the Virgo filaments, Virgo cluster, and field, respectively, using the BPT diagram constructed from the SDSS spectroscopic data. The SFDGs were divided into two subsamples of E-SFDGs and L-SFDGs based on their morphologies as classified by visual inspection of SDSS images. We derived gas-phase metallicities (i.e., O/H) and NUV SFRs of the SFDGs using the SDSS spectroscopic and GALEX UV photometric data, respectively.
2. We found that SFDGs in the Virgo filaments show different distributions of O/H versus stellar mass and sSFR versus stellar mass from those in the Virgo cluster. The SFDGs in the Virgo filaments deviate toward lower O/H values and higher sSFRs than those in the Virgo cluster at a given stellar mass. However, SFDGs in the Virgo filaments exhibit similar distributions to those in the field without showing a significant systematic difference.
3. The majority of the SFDGs in the Virgo cluster is located in outskirts (i.e., \( R_{\text{vir}} \)) of the cluster. Two subsamples of the SFDGs in the Virgo cluster located inside and outside of one \( R_{\text{vir}} \) of the Virgo cluster show no distinct difference in the O/H versus stellar mass and sSFR versus stellar mass distributions. These results suggest that ram pressure does not play an essential role in the chemical properties and star formation activity of the SFDGs in the Virgo cluster.
4. We inspected the perturbation parameter \( f \) value distributions of the SFDGs in the Virgo filaments and Virgo cluster, which provide insights into the effectiveness of interactions between galaxies and the local environments of the SFDGs. We found that the SFDGs in the Virgo cluster exhibit a skewed distribution toward higher \( f \) values, whereas the SFDGs in the Virgo filaments have a lower peak. This leads to the proposal that tidal interactions between galaxies could be a possible primary process in the metallicity enhancement and star formation suppression of the SFDGs in the Virgo cluster.
5. The SFDGs in the Virgo III filament appear to have O/H and sSFR distributions similar to those of the Virgo cluster, whereas the SFDGs in the other four filaments show field-like distributions. We also found that the \( f \) value distribution of the SFDGs in the Virgo III filament is remarkably similar to that of the Virgo cluster, where a large fraction of the SFDGs have high \( f \) values. We propose that the SFDGs in the Virgo III filament are in a different local environment from those in the other four filaments, but they are somewhat comparable to the Virgo cluster, where tidal interactions between galaxies occur more frequently. The similarity of chemical properties and star formation activities of the SFDGs in the Virgo III filament with their counterparts in the Virgo cluster indicates that a significant fraction of the SFDGs in the Virgo III filament may have already been chemically preprocessed before they fell into the Virgo cluster.
6. We found that E-SFDGs are chemically evolved objects with low active star formation in the Virgo filaments and Virgo cluster. The O/H and sSFR distributions of E-SFDGs in the Virgo III filament are similar to those of the Virgo cluster. Moreover, about half of the SFDGs in the Virgo III filament are E-SFDGs, whereas other filaments contain very small fractions of E-SFDGs. We propose that these E-SFDGs are transitional dwarf galaxies on the way to transforming into red, quiescent dEs from late-type galaxies. The tidal interactions between galaxies in the filaments could be the most probable formation mechanism of these galaxies. We also suggest that galaxy mergers may be an additional formation channel for at least some E-SFDGs in the filament.

Consequently, we emphasize that SFDGs in different local environments are well separated with respect to their properties. The SFDGs associated with tidal interactions are more evolved transitional objects, characterized by chemical enhancement, suppressed star formation, and early-type morphologies. Therefore, we propose that pre-processing depends mainly on the small-scale local environments of the filaments, which is in line with the suggestion of local galaxy density as the main parameter of pre-processing (Castignani et al. 2021).

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