



# Environmental Effects in Herschel Observations of the Ionized Carbon Content of Star-forming Dwarf Galaxies in the Virgo Cluster\*

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## Abstract

We use archival Herschel data to examine the singly ionized carbon ([C II]) content of 14 star-forming dwarf galaxies in the Virgo cluster. We use spectral energy distribution fits to far-infrared, mid-infrared, near-infrared, optical, and ultraviolet data to derive the total infrared continuum (TIR) for these galaxies. We compare the [C II]/TIR ratio for dwarf galaxies in the central part of Virgo to those in the southern part of the cluster and to galaxies with similar TIR luminosities and metallicities in the Herschel Dwarf Galaxy Survey (DGS) sample of field dwarf galaxies to look for signs of [C II] formation independent of star formation. Our analysis indicates that the sample of Virgo dwarfs in the central part of the cluster has significantly higher values of [C II]/TIR than the sample from the southern part of the cluster and the sample from the DGS, while the southern sample is consistent with the DGS. This [C II]/TIR excess implies that a significant fraction of the [C II] in the dwarf galaxies in the cluster center has an origin other than star formation and is likely to be due to environmental processes in the central part of the cluster. We also find a surprisingly strong correlation between [C II]/TIR and the local ram pressure felt by the dwarf galaxies in the cluster. In this respect, we claim that the excess [C II] we see in these galaxies is likely to be due to formation in ram-pressure shocks.

*Unified Astronomy Thesaurus concepts:* [Virgo Cluster \(1772\)](#); [Ram pressure stripped tails \(2126\)](#); [Far infrared astronomy \(529\)](#); [CII region \(232\)](#); [Dwarf galaxies \(416\)](#)

## 1. Introduction

The [C II] line at 158  $\mu\text{m}$  is commonly used in local galaxies (including our own Milky Way) as a measure of their star-formation rate (SFR), e.g., Stacey et al. (1991), Malhotra et al. (2001), De Looze et al. (2011, 2014), Díaz-Santos et al. (2014), Pineda et al. (2014), Herrera-Camus et al. (2015), Sutter et al. (2019). There has also been interest in its use as an SFR tracer at high redshifts, where it is accessible to ALMA, e.g., Capak et al. (2015), Camiani et al. (2018), Ferrara et al. (2019), Le Fèvre et al. (2020), Schaerer et al. (2020), Romano et al. (2022). This has revived interest in determining circumstances where environmental factors might cause departures from the [C II]–SFR correlation. Recent studies with the FIFI-LS instrument onboard the Stratospheric Observatory for Infrared Astronomy (SOFIA) have shown that turbulence in the interstellar medium (ISM) associated with interactions with jets can lead to the formation of [C II] distinct from star-formation processes. As the infrared continuum also traces star formation (albeit only obscured star formation, while the [C II] can, in principle, reflect both the obscured star formation and the unobscured star formation traced by ultraviolet emission), and [C II] associated with star formation is excited via gas heated by the photoelectric effect of UV photons on small dust grains and polycyclic aromatic hydrocarbons (e.g.,

Herrera-Camus et al. 2015), [C II] from other sources is identifiable as an excess in the [C II]/infrared continuum ratio, as seen in the host galaxies of active galactic nuclei (AGN) where the jet is interacting with the disk (Appleton et al. 2018; Smirnova-Pinchukova et al. 2019; Fadda et al. 2021). Similarly, Herschel observations of gas in the collisionally formed bridge between the Taffy Galaxies (UGC 12914/12915) found enhanced [C II]/infrared continuum ratios that were attributed to turbulently heated H<sub>2</sub> and high column-density HI resulting from the collision of the two galaxies (Peterson et al. 2018), and models of warm molecular gas shocks in Stephan's Quintet point to collisional heating from the warm H<sub>2</sub> being responsible for boosting the [C II] emission in that system (Appleton et al. 2013, 2017).

Galaxies in clusters are affected by environmental processes including interactions with other galaxies and with the intra-cluster medium (ICM). The interaction of the ISM of galaxies with the ICM ram pressure can cause shocks at the “bows” of the galaxies as well as stripping of their gas, a process known as ram-pressure stripping (Gunn & Gott 1972). As [C II] can be formed in shocks, it has long been speculated that it could be formed by ram-pressure processes, e.g., by Pierini et al. (1999) who found (using the Infrared Space Observatory, ISO; Kessler et al. 1996) that NGC 4522 had an “exceptional” value of [C II]/TIR, which they ascribed to it probably experiencing ram-pressure stripping from the Virgo cluster ICM (NGC 4522 has since been confirmed as being subject to ram-pressure stripping, e.g., Kenney et al. 2004; Chung et al. 2007). However, observations of 19 late-type galaxies in Virgo by Leech et al. (1999), also using ISO, found that the influence of the cluster environment on the [C II] emission was small compared to its dependence on other factors. This seemed to

\* Herschel is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.

**Table 1**

Literature Data on the Sample: Position and Distance from GOLDMine (Gavazzi et al. 2014), Metallicity from Grossi et al. (2016), and Systemic Velocity from Haynes et al. (2018)

Galaxy ID	R.A. (J2000)	Decl. (J2000)	Distance (Mpc)	Metallicity ( $12 + \log(\text{O}/\text{H})$ )	Velocity (km/s)
VCC 144	12:15:18.3	+05:45:39.8	32	$8.21 \pm 0.10$	$2016 \pm 32$
VCC 213	12:16:56.0	+13:37:31.5	17	$8.77 \pm 0.12$	$-164 \pm 61$
VCC 324	12:19:09.9	+03:51:23.4	17	$8.14 \pm 0.10$	$1525 \pm 23$
VCC 334	12:19:14.2	+13:52:55.9	17	$8.22 \pm 0.10$	$-252 \pm 21$
VCC 340	12:19:22.1	+05:54:37.7	32	$8.26 \pm 0.10$	$1510 \pm 28$
VCC 562	12:22:35.9	+12:09:29.2	17	$8.10 \pm 0.10$	$9 \pm 22$
VCC 693	12:24:03.2	+05:10:50.2	17	$8.43 \pm 0.10$	$2051 \pm 50$
VCC 699	12:24:07.4	+06:36:26.9	23	$8.30 \pm 0.10$	$727 \pm 43$
VCC 737	12:24:39.5	+03:59:43.8	17	$8.28 \pm 0.10$	$1725 \pm 78$
VCC 841	12:25:47.5	+14:57:06.8	17	$8.33 \pm 0.10$	$499 \pm 20$
VCC 1437	12:33:15.4	+09:10:25.2	17	$8.38 \pm 0.10$	$1155 \pm 29$
VCC 1575	12:34:39.5	+07:09:36.7	17	$8.76 \pm 0.10$	$593 \pm 44$
VCC 1686	12:24:43.4	+13:15:33.6	17	$8.33 \pm 0.15$	$1120 \pm 53$
VCC 1725	12:37:41.5	+08:33:31.1	17	$8.25 \pm 0.10$	$1076 \pm 38$

rule out any large-scale environmental effect in Virgo, despite the anomalously high [C II] value found for NGC 4522.

In this study, we look at 14 dwarf galaxies in the Virgo cluster that have been observed in [C II] with the PACS instrument on the Herschel space telescope (Pilbratt et al. 2010; Poglitsch et al. 2010) to see whether there is any excess in [C II]/infrared continuum that can be attributed to environmental effects injecting energy into the ISM. These observations are more sensitive than the earlier ISO observations,<sup>4</sup> while the galaxies studied here are smaller than those observed by Leech et al. (1999); as dwarf galaxies are known to be more affected by ram pressure than larger galaxies (Boselli et al. 2014) they may thus be more prone to environmental influences in their integrated [C II] signal.

## 2. Sample and Analysis

The sample analyzed here was extracted from the Herschel Science Archive by searching the archive for dwarf galaxies observed in the [C II] line in or near the Virgo cluster. The observations that were found were all from a single project, drawn from the star-forming dwarf galaxies in Virgo studied by Grossi et al. (2015) and Grossi et al. (2016). This gives a sample for which far-infrared (FIR) continuum data, which are essential for the modeling used to determine the total infrared flux (TIR), and metallicities, which are needed for identifying suitable comparator galaxies, are available. Basic information from the literature for the galaxies in the sample is given in Table 1.

### 2.1. Herschel [C II] Intensity Maps and Spectra

Data were downloaded from the Herschel Science Archive in the form of fully calibrated and flat-fielded Level 2 products output by the PACS pipeline reduction.<sup>5</sup>

The Herschel [C II] data cubes were analyzed using SOSPEX (Fadda & Chambers 2018). Spatially integrated spectra were created in SOSPEX using an aperture that took in the whole map and line profiles were fitted to these spectra in SOSPEX

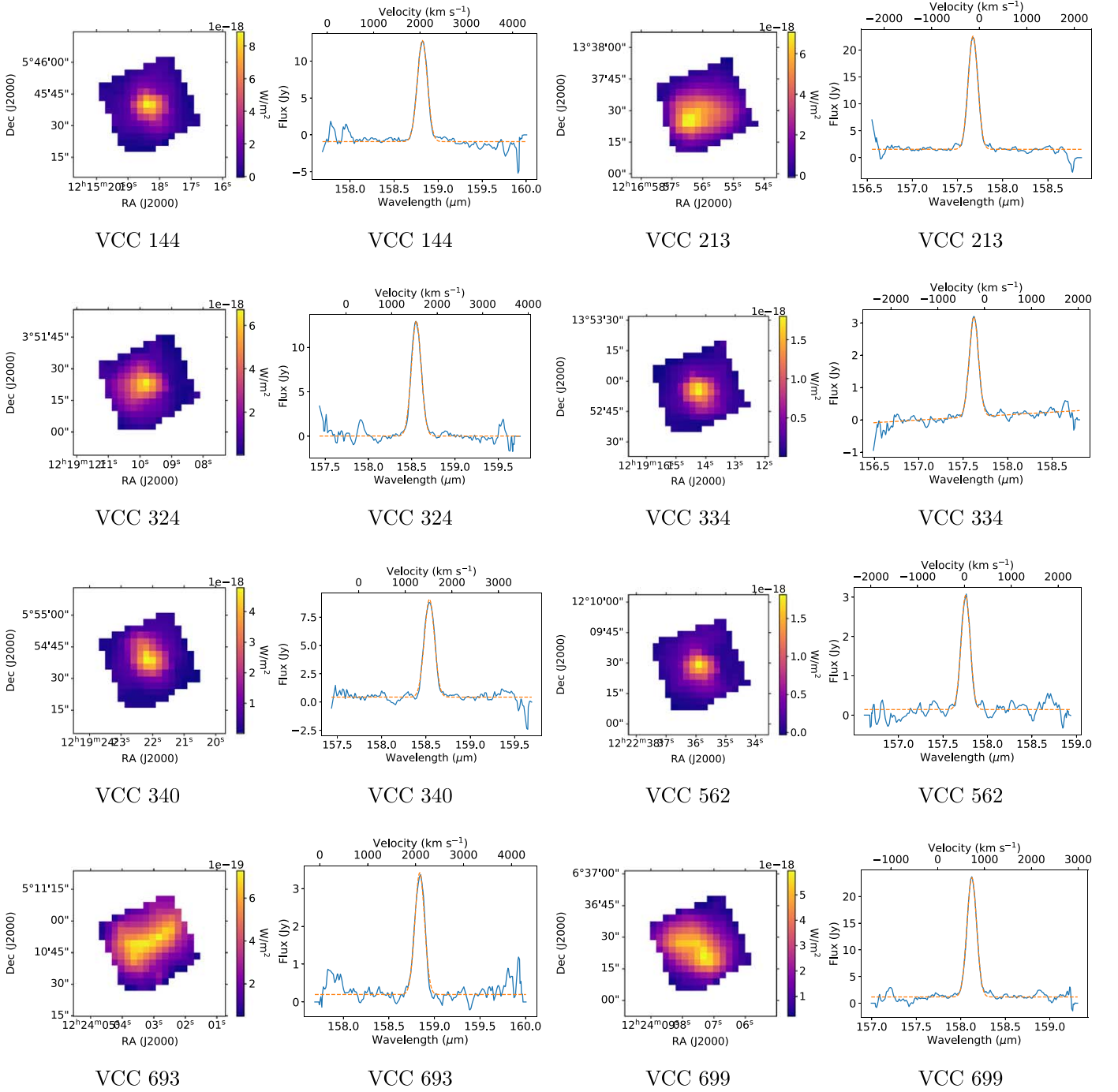
using Gaussian profiles; baseline regions were defined visually to be clear of the emission lines and of the noisy end regions of the spectra. These fits were used to obtain the integrated [C II] flux and its associated error. With the exceptions of VCC 334, VCC 737, and VCC 1725, baselines were assumed to be flat and were set to the median of the data (excluding the line region and the noisy ends of the spectra). For the three galaxies mentioned, visual inspection showed that the flat baseline initially fitted was not a good match for the actual spectral baseline. These three galaxies were fitted with a sloped baseline: for VCC 737 this reduced the line flux by 4% while, for VCC 334 and VCC 1725, the reduction was less than 1% and was within the measurement errors. The fitted line profile is shown together with the spectrum in Figure 1. The values of the [C II] intensity derived from these fitted line profiles are used for the rest of the analysis presented here (see Table 2). Line maps were created using line fitting to each pixel in SOSPEX. The line maps are used to illustrate and examine the extent of the [C II] but measurements taken from these maps were not used in the analysis presented here.

### 2.2. Spectral Energy Distribution Fitting

Spectral Energy Distributions (SEDs) were created using FIR data from the Herschel Virgo Cluster Survey (HeVICS; Auld et al. 2013), as reanalyzed by Grossi et al. (2015), mid-infrared data from AllWISE (Wright et al. 2010; Cutri et al. 2013), and optical data from the SDSS/Extended Virgo Cluster Catalogue (EVCC; Kim et al. 2014), supplemented with our own analysis of near-infrared data from 2MASS (Skrutskie et al. 2006) and UV data from GALEX (Morrissey et al. 2007). For VCC 1686, which has a foreground star superposed on the galaxy, we used our own measurement from the AllWISE data and the SDSS fluxes, masking out the star and patching the region with a similar region from elsewhere in the galaxy. We also used our own measurement of the SDSS  $z$  band flux of VCC 693, as the literature value from Kim et al. (2014) was highly discrepant from the other fluxes (and our measurement) for unknown reasons. Errors were calculated following the prescriptions given in the documentation in the archives, or following Kim et al. (2014) for the SDSS. Absorption corrections to the UV, optical, and NIR fluxes were made using the dust measurements of Schlafly & Finkbeiner (2011),

<sup>4</sup> Errors on the [C II] fluxes here range from 0.3 to  $1.8 \times 10^{-18} \text{ W m}^{-2}$ , compared to 2 to  $7 \times 10^{-17} \text{ W m}^{-2}$  in Leech et al. (1999).

<sup>5</sup> Herschel Science Archive data products are described at <https://www.cosmos.esa.int/web/herschel/data-products-overview>.



**Figure 1.** Herschel [C II] line intensity maps and spatially integrated spectra for the fourteen galaxies in the sample. Spectra show the Herschel spectrum (solid blue line) and the fitted line profile from SOSPEX (orange dashed line).

via the IRSA Galactic Dust Reddening and Extinction service.<sup>6</sup> As the galaxies in this sample are similar in size to or smaller than the beam (i.e., are point sources) for the crucial Herschel measurements of the FIR fluxes, it is not reliable to use a single aperture to measure the SED. We therefore use the integrated whole-galaxy flux at all wavelengths rather than attempting to make measurements within a defined aperture.

SED fitting was carried out using MAGPHYS (Multi-wavelength Analysis of Galaxy Physical Properties; da Cunha et al. 2008) which returns both an overall best-fit SED and

marginalized probability distributions for the individual parameters. Fluxes and errors, both converted to Jy, were supplied as inputs to the fitting, either from the literature or based on our own measurements as described above (see Table A1). The plots in Figure 2 show the overall best-fit SED output by MAGPHYS; for our analysis, we use the marginalized probabilities for  $L_d^{\text{tot}}$  (the MAGPHYS parameter that gives the TIR) using the 50% point of the probability distribution as the central estimator and the 16% and 84% points as the estimators for the  $1\sigma$  error. The difference between the value of  $L_d^{\text{tot}}$  returned for the best-fit model and the 50% point of the probability distribution of  $L_d^{\text{tot}}$  is less than  $1\sigma$  (or less than 1% in the cases where the error estimate is zero) except

<sup>6</sup> <https://irsa.ipac.caltech.edu/applications/DUST/>

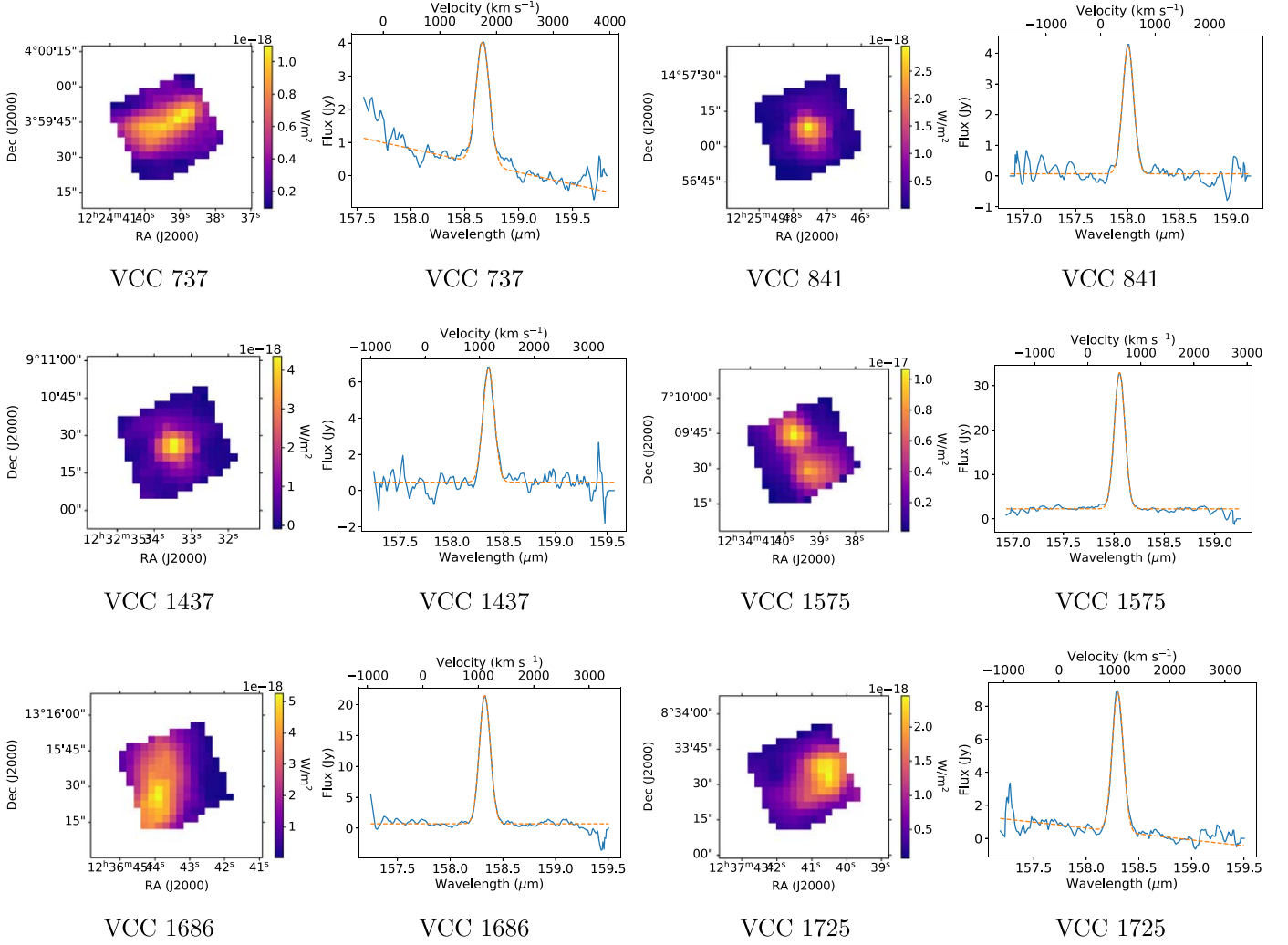


Figure 1. (Continued.)

for VCC 562 (best-fit  $L_d^{\text{tot}}$  0.05 dex higher) and VCC 841 (best-fit  $L_d^{\text{tot}}$  0.21 dex higher).

### 2.3. Results

The results of the [C II] observations and the SED fitting are given in Table 2. Figure 3 shows how the [C II]/TIR ratio varies with angular distance from the giant elliptical M87 (taken to represent the cluster center), while Figure 4 shows the positions of the sources within the cluster. The values of  $L_{\text{TIR}}$  are calculated from the MAGPHYS output of  $L_d^{\text{tot}}$  assuming a distance of 17 Mpc except for three galaxies that, as given in Table 1, are assigned to more distant subclusters in Virgo at 23 Mpc (VCC 699) and 32 Mpc (VCC 144 and VCC 340); no error on the distance is assumed.

For the purpose of our analysis, we divide the sample into two groups: the central galaxies (VCC 213, VCC 334, VCC 562, VCC 841, and VCC 1686), which lie around M87 and are all north of decl.  $+12^\circ$ , and the southern galaxies (VCC 144, VCC 324, VCC 340, VCC 693, VCC 699, VCC 737, VCC 1437, VCC 1575, and VCC 1725), which are all south of decl.  $+9^\circ.5$  and lie around or south of M49. The central galaxies thus correspond to subcluster A and the southern galaxies to subcluster B, with the exception of VCC 699 (W' cloud) and VCC 144 and 340 (W cloud), according to the standard

subdivision of Virgo (e.g., Boselli et al. 2014). The southern galaxies thus combine three different environments, but as these form our control sample of galaxies outside of the center of the Virgo cluster this is not expected to affect our analysis.

## 3. Discussion

### 3.1. Differences between the Samples

The “central” galaxies are those closest to the center of the Virgo cluster while the “southern” galaxies form a control sample away from the cluster core, thus if there is any environmental effect it should manifest as a difference between these two samples. Comparator galaxies from the Herschel Dwarf Galaxies Survey (DGS; Cormier et al. 2015) are also used as to form a second control sample. The TIR for the DGS galaxies is, as with our galaxies, defined using the modeled dust SED and their measurement over 1–1000  $\mu\text{m}$  can be expected to give an equivalent measurement of the total infrared flux to the MAGPHYS measurement over 3–1000  $\mu\text{m}$  (da Cunha et al. 2008; Rémy-Ruyer et al. 2015, particularly Section 4.2 and Table 3). As the [C II]/TIR ratio is influenced by both metallicity and FIR luminosity (e.g., Cormier et al. (2015), Figure 5), we take a subsample of DGS galaxies that have similar metallicities ( $12 + \log(\text{O}/\text{H}) = 8.0\text{--}8.8$ ) and

**Table 2**  
Measured Values for The Galaxies from The [C II] Observations and The SED Fitting

Galaxy ID	Herschel (C II) OBSID	(C II) flux ( $10^{-18}$ W m $^{-2}$ )	TIR Luminosity $\log(L_{\text{TIR}}/\mathcal{L}_{\odot}^{\text{N}})$	TIR flux ( $10^{-15}$ W m $^{-2}$ )	(C II)/TIR (%)
VCC 144	1342224404	$232.8 \pm 1.6$	$9.28^{+0.05}_{-0.01}$	$60.2^{+8.1}_{-0.7}$	$0.387^{+0.005}_{-0.052}$
VCC 213	1342224405	$338.4 \pm 1.4$	$8.68^{+0.04}_{-0.02}$	$53.0^{+5.8}_{-2.4}$	$0.638^{+0.029}_{-0.070}$
VCC 324	1342225152	$217.9 \pm 1.8$	$8.90^{+0.00}_{-0.01}$	$88.0^{+0.0}_{-1.0}$	$0.248^{+0.003}_{-0.002}$
VCC 334	1342225154	$48.6 \pm 0.3$	$7.94^{+0.00}_{-0.00}$	$9.6^{+0.1}_{-0.0}$	$0.504^{+0.003}_{-0.007}$
VCC 340	1342225156	$147.4 \pm 1.1$	$8.89^{+0.02}_{-0.00}$	$24.2^{+0.9}_{-0.3}$	$0.608^{+0.008}_{-0.022}$
VCC 562	1342225158	$44.5 \pm 0.5$	$8.01^{+0.04}_{-0.06}$	$11.2^{+1.2}_{-1.4}$	$0.397^{+0.051}_{-0.044}$
VCC 693	1342225160	$50.9 \pm 0.5$	$8.33^{+0.01}_{-0.00}$	$23.7^{+0.6}_{-0.0}$	$0.215^{+0.002}_{-0.005}$
VCC 699	1342225162	$363.6 \pm 1.9$	$9.18^{+0.00}_{-0.00}$	$91.1^{+0.0}_{-0.0}$	$0.399^{+0.002}_{-0.002}$
VCC 737	1342225165	$70.6 \pm 0.7$	$7.79^{+0.00}_{-0.00}$	$6.8^{+0.0}_{-0.1}$	$1.046^{+0.016}_{-0.011}$
VCC 841	1342225166	$67.6 \pm 0.7$	$7.82^{+0.04}_{-0.01}$	$7.2^{+0.7}_{-0.2}$	$0.934^{+0.023}_{-0.091}$
VCC 1437	1342225221	$103.7 \pm 1.5$	$8.35^{+0.01}_{-0.08}$	$24.8^{+0.6}_{-4.4}$	$0.418^{+0.075}_{-0.011}$
VCC 1575	1342225223	$486.5 \pm 1.5$	$9.11^{+0.00}_{-0.00}$	$141.1^{+0.0}_{-0.0}$	$0.345^{+0.001}_{-0.001}$
VCC 1686	1342225225	$324.8 \pm 1.3$	$8.67^{+0.01}_{-0.00}$	$51.8^{+0.6}_{-0.6}$	$0.627^{+0.008}_{-0.008}$
VCC 1725	1342225226	$133.5 \pm 0.8$	$8.54^{+0.00}_{-0.00}$	$38.4^{+0.0}_{-0.0}$	$0.348^{+0.002}_{-0.002}$

luminosities ( $L_{\text{TIR}}/\mathcal{L}_{\odot}^{\text{N}} = 5 \times 10^7 - 2.5 \times 10^9$ ) to those of the Virgo dwarfs.

Four of the five central galaxies have [C II]/TIR  $> 0.5\%$  compared to two out of nine in the southern region and two out of eight in the DGS comparator subsample. We compare the various samples statistically both by looking at their averages and by using the Kolmogorov–Smirnov test; as we are testing the hypothesis that the central galaxies have a higher [C II]/TIR than those in the control samples we use the single-sided two-sample Kolmogorov–Smirnov test. The distribution of the samples in [C II]/TIR,  $L_{\text{TIR}}$  and metallicity is shown in Figure 5. Including the full DGS sample (shown in Figure 5 by red squares), with a mean [C II]/TIR of  $0.29 \pm 0.02$ , leads to a very significant difference between our central sample and the DGS ( $3.5\sigma$ ;  $p = 0.001$  from the Kolmogorov–Smirnov test), but also to a significant difference appearing between our southern sample and the DGS ( $1.9\sigma$ ;  $p = 0.02$  from the Komogorov–Smirnov test) due to the inclusion of a large number of galaxies that are not similar to the Virgo dwarfs, motivating us to use only a subsample of DGS galaxies with similar luminosities and metallicities for our comparison sample.

The central galaxies have a mean [C II]/TIR of  $0.62\% \pm 0.09\%$  and the southern galaxies have a mean [C II]/TIR of  $0.45\% \pm 0.08\%$ , indicating a  $1.4\sigma$  difference between these two samples (errors on the means in both cases estimated by propagating the errors on the individual measurements in the samples and combining these in quadrature with the uncertainty in the estimates of the means due to the scatter in the samples). This is confirmed by the one-sided Kolmogorov–Smirnov test, which, despite the small sizes of the samples, gives a likelihood of getting this distribution if both were drawn from the same parent population of  $p = 0.086$ . Similarly, the DGS subsample has a mean [C II]/TIR of  $0.37\% \pm 0.05\%$ , indicating a  $2.4\sigma$  difference from the central sample, and the Kolmogorov–Smirnov test gives  $p = 0.040$ . The difference between the means of the DGS subsample and the southern sample is  $0.8\sigma$  and the Kolmogorov–Smirnov test gives  $p = 0.57$ , both consistent with the DGS subsample and the southern Virgo dwarfs being drawn from the same parent population. We therefore combine these two control samples, getting a mean of  $0.41 \pm 0.05$ , giving a difference of  $2.0\sigma$  from

the mean of the central sample, and a result from the Kolmogorov–Smirnov test of  $p = 0.032$ . We conclude that both parametric and nonparametric tests show that there is a statistically significant difference between [C II]/TIR in the central sample and the control samples, with the caveat that the numbers in the samples remain small. The results of these statistical tests for difference are summarized in Table 3.

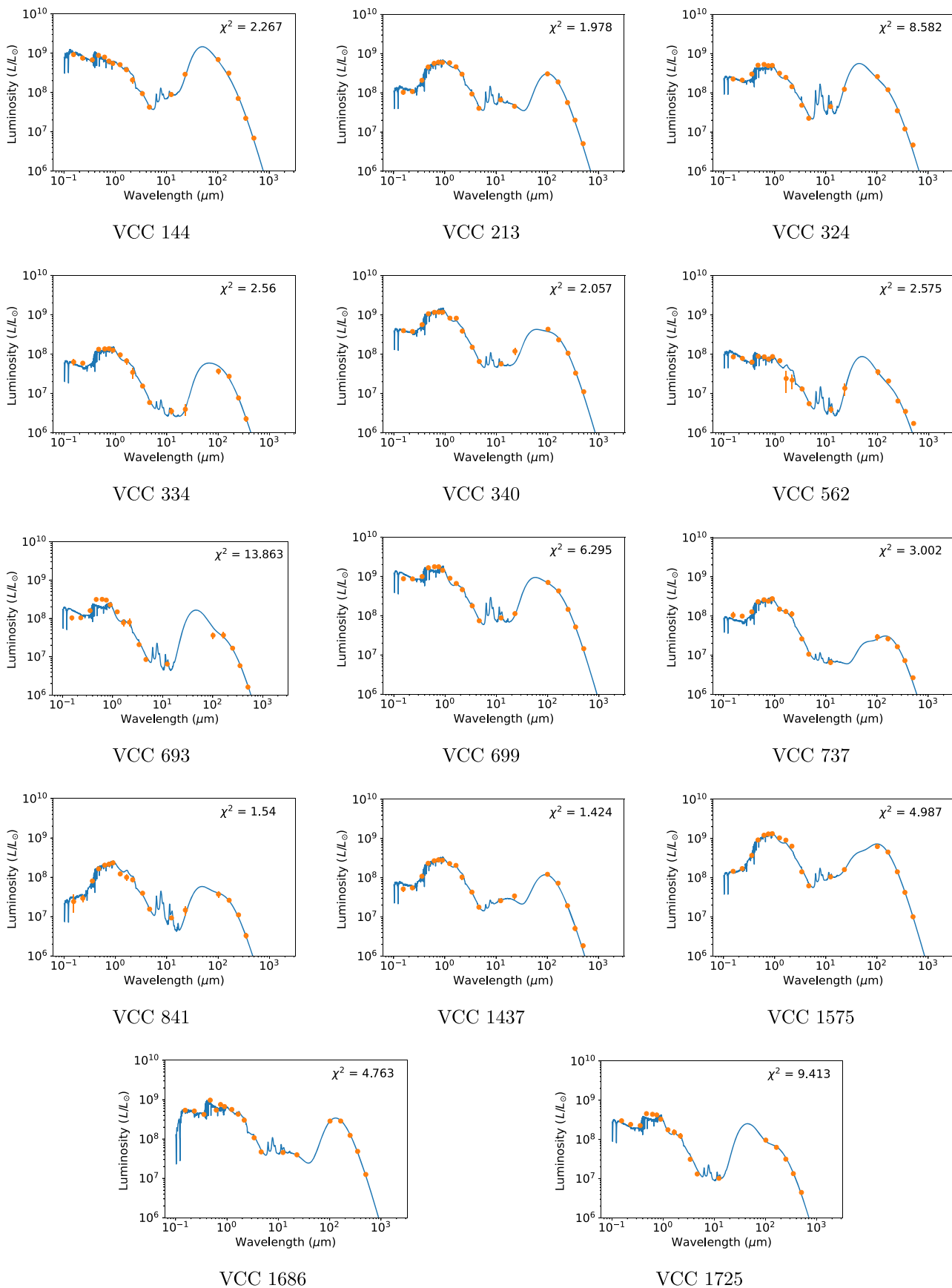
### 3.2. Relationship to Ram-pressure Stripping

We compare our sample to the work of Köppen et al. (2018) to see whether galaxies with high values of [C II]/TIR correspond to those identified there as likely to be undergoing ram-pressure stripping. Köppen et al. (2018) categorize galaxies as “active strippers” (likely to be currently undergoing ram-pressure stripping) and “past strippers” (showing evidence of past gas loss, but not currently undergoing ram-pressure stripping) based on an analysis of how tightly bound their HI disk is and whether the local ram pressure would be sufficient to strip this. The local ram pressure,  $p_{\text{loc}}$ , is expected to decrease with increasing distance from the cluster center (see Figure 14 in Köppen et al. 2018). This pressure is fundamentally related to two parameters: the density of the ICM and the speed with which a galaxy is moving through that ICM, with  $p_{\text{loc}} = \rho_{\text{ICM}} v_{\text{gal}}^2$ .

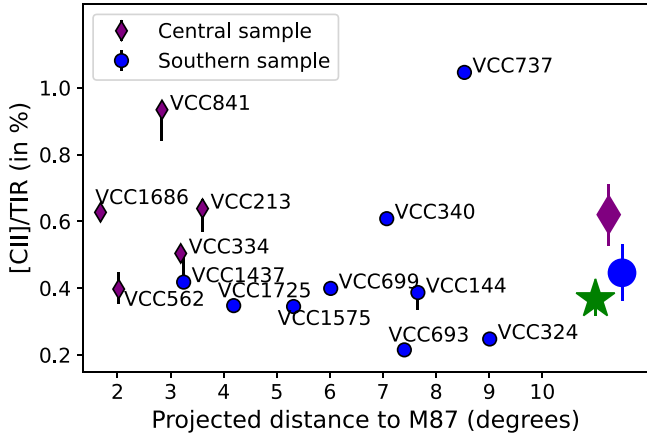
Köppen et al. (2018) use a  $\beta$  model of the cluster (Cavaliere & Fusco-Femiano 1976; Schindler et al. 1999; Vollmer et al. 2001) to estimate the ICM density and the cluster mass distribution:

$$\rho = \rho_0 \left( 1 + \frac{r^2}{r_c^2} \right)^{-(3/2)\beta}. \quad (1)$$

The values adopted for the  $\beta$  model parameters in Köppen et al. (2018) are  $\beta = 0.47$ ,  $r_c = 13.4$  kpc, and  $\rho_0 = 4 \times 10^{-2}$  cm $^{-3}$  for the ICM, and  $\beta = 1$ ,  $r_c = 0.32$  Mpc, and  $\rho_0 = 3.8 \times 10^{-4}$   $\mathcal{M}_{\odot}^{\text{N}}$  pc $^{-3}$  for the dark matter cluster halo. The velocities of the galaxies at a given radius are estimated as being the local escape velocity using the  $\beta$  model with the parameters for the dark matter halo given above to estimate the mass distribution. There are limitations to this approach: the  $\beta$  model assumes a smooth, symmetrical relationship with radius,



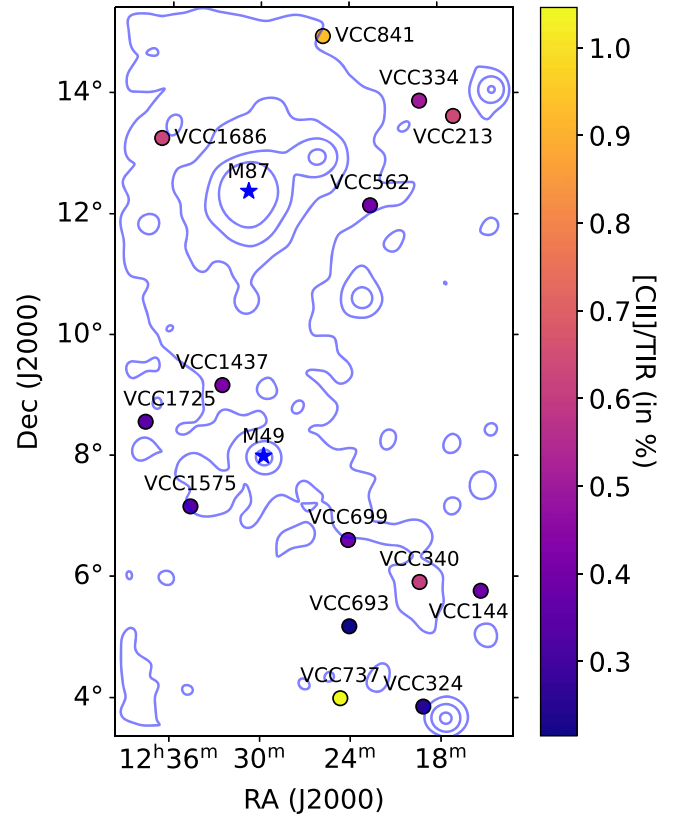
**Figure 2.** Spectral Energy Distributions of the 14 galaxies in the sample. Measured data points are shown as orange circles; error bars are shown on these data points but may be smaller than the symbol used. The best-fit SED from MAGPHYS is shown as a solid blue line with its  $\chi^2$  given in the upper-right.



**Figure 3.**  $[C\ II]/TIR$  vs. projected distance to M87, the central elliptical galaxy in the Virgo cluster. Error bars indicate  $1\sigma$  errors based on the Herschel  $[C\ II]$  error budget and the 16%–84% range of the marginalized probability distribution of the TIR flux; larger errors are dominated by the uncertainty in the TIR flux. Points indicate the central value of  $[C\ II]/TIR$ , based on the 50% point of the marginalized probability distribution; shape and color indicate the sample to which each galaxy is assigned: central (purple lozenges) or southern (blue circles). The large symbols (shown for illustrative purposes on the right-hand side) indicate the arithmetic mean and error of  $[C\ II]/TIR$  for each sample, with the large green star showing the mean and error for the comparator sample drawn from the Herschel Dwarf Galaxy Survey (see Section 3.1).

not taking into account structures and variations in the density, and subclusters, while the assumption that galaxies are moving at their local escape velocity may not be true for individual galaxies; however, it provides a reasonable description overall. They also define  $p_{\text{def}}$  as the pressure required to strip the galaxy to its current H I deficiency, with the ratio  $p_{\text{loc}}/p_{\text{def}}$  then giving whether a galaxy is currently being stripped (an “active stripper,” with  $p_{\text{loc}}/p_{\text{def}} > 0.5$ ) or was stripped in the past (a “past stripper,” with  $p_{\text{loc}}/p_{\text{def}} < 0.5$ ). We look here first at how their analysis compares to our data and then at how  $p_{\text{loc}}$ , calculated for our galaxies, corresponds to  $[C\ II]/TIR$ .

A comparison of their analysis with our data does not reveal any firm correlation between high values of  $[C\ II]/TIR$  and whether a galaxy is identified as likely to be undergoing ram-pressure stripping: of the galaxies in the central sample with values for  $[C\ II]/TIR > 0.5\%$ , only VCC 1686 is an “active stripper” while VCC 213 and VCC 334 are both given as “past strippers” and VCC 841 is not listed in their sample. The only galaxy in the central sample with a value for  $[C\ II]/TIR < 0.5\%$ , VCC 562, is also not listed. For the southern sample, of the two galaxies with values for  $[C\ II]/TIR > 0.5\%$ , VCC 737 is a “past stripper” while VCC 340 is not listed; while among the galaxies with values for  $[C\ II]/TIR < 0.5\%$ , VCC 1437 is an “active stripper,” VCC 324, 693, 699, 1575, and 1725 are “past strippers,” and VCC 144 is not listed. Figure 6 gives the distribution of  $[C\ II]/TIR$  for the sources in our sample assigned to each category by Köppen et al. (2018) with the  $x$ -axis showing their  $p_{\text{loc}}/p_{\text{def}}$ , with their break of  $p_{\text{loc}}/p_{\text{def}} = 0.5$  as the demarcation between the active and past strippers marked. It can be seen that there is no significant difference between the mean  $[C\ II]/TIR$  for the “active strippers” and the “past strippers.” Further to this, we find a Spearman’s  $\rho = 0.38$  giving, with 10 pairs, a significance of  $p = 0.28$ ; while if the outlier VCC 737 is ignored we find  $\rho = 0.40$  which, with 9 pairs, gives a significance of  $p = 0.29$ . This implies there is no significant correlation between  $[C\ II]/TIR$  and  $p_{\text{loc}}/p_{\text{def}}$ .



**Figure 4.** Positions of sample galaxies in the cluster with the central value for  $[C\ II]/TIR$  indicated by the color. The positions of M87 and M49 are indicated by blue stars. Contours (at 0.1, 0.2, 0.4, and 0.8 counts  $\text{s}^{-1} \text{pixel}^{-1}$ ) indicate the smoothed hard X-ray counts from the ROSAT All Sky Survey (Voges et al. 1999).

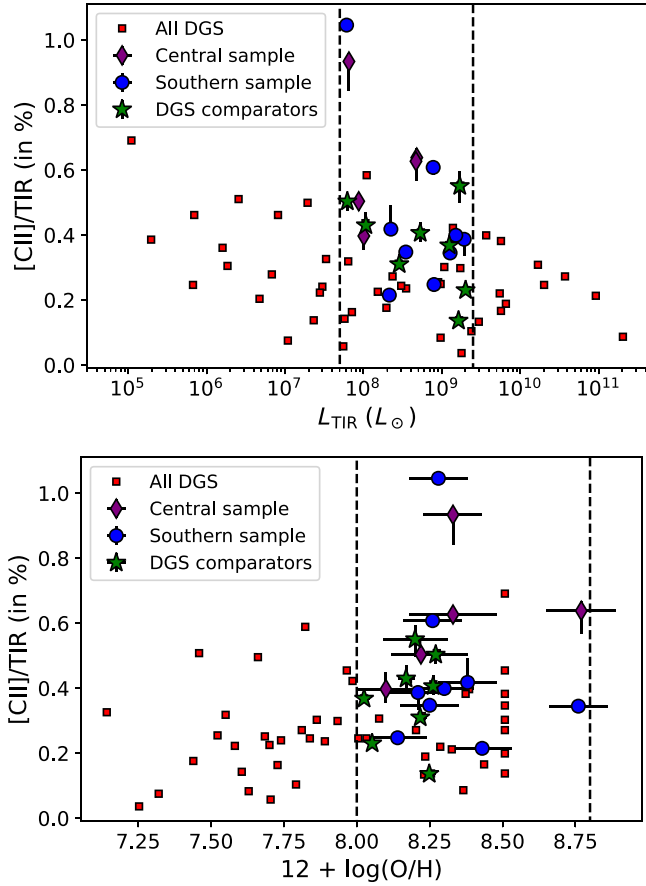
**Table 3**

Summary of the Samples: Number, Mean, One-Sided Kolmogorov–Smirnov  $p$  Value and Statistic for Difference from the Central Galaxies, and the Significance of the Difference in the Mean from the Central Galaxies

Sample	$N$	Mean	KS $p$ value	KS statistic	$\sigma$
Central	5	$0.62 \pm 0.09$	...	...	...
Southern	9	$0.45 \pm 0.08$	0.086	0.58	1.4
DGS	8	$0.37 \pm 0.05$	0.040	0.68	2.4
Southern+DGS	17	$0.41 \pm 0.05$	0.032	0.62	2.0

This lack of a correlation may be partly explained by the effect of stripping on star formation. Grossi et al. (2015), from where the sample here is ultimately drawn, reported that the dwarfs in their sample that were undetected in HeViCS far-infrared continuum observations had a larger fraction of object with higher H I deficiencies than their detected dwarfs. While this is not a very strong effect, if stripped galaxies are less likely to be forming stars, then they are less likely to have been observed in this sample. This does not, however, look to be sufficient to explain the lack of correlation we see here, particularly as we do have both “active strippers” and “past strippers” in both samples.

A second effect that may lend an explanation, which is clear from Köppen et al. (2018), is that whether a galaxy is undergoing ram-pressure stripping depends both on the pressure it is feeling from the ICM (their  $p_{\text{loc}}$ ) and the pressure needed to strip its neutral hydrogen (their  $p_{\text{def}}$ ). A galaxy where  $p_{\text{def}}$  is substantially higher than  $p_{\text{loc}}$  will not currently be

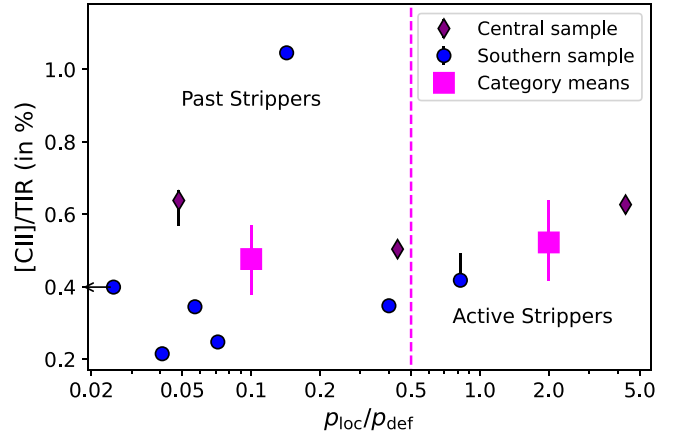


**Figure 5.**  $[C II]/TIR$  vs.  $L_{TIR}$  (upper) and metallicity (lower) for our central galaxies (purple lozenges) and southern galaxies (blue circles) along with the comparator subsample from the DGS (green stars). Red squares indicate the other DGS galaxies and the black dashed lines indicate the limits for our selection in  $L_{TIR}$  and metallicity.

undergoing ram-pressure stripping, even if the value of  $p_{loc}$  is higher than for “active strippers.” For example, VCC 1437, identified as an “active stripper,” has  $p_{loc} = 230 \text{ cm}^{-3} (\text{km s}^{-1})^2$  and  $p_{def} = 280 \text{ cm}^{-3} (\text{km s}^{-1})^2$  while VCC 334, identified as a “past stripper” at almost the same distance from M87, has  $p_{loc} = 240 \text{ cm}^{-3} (\text{km s}^{-1})^2$  (that is, marginally higher than for VCC 1437) but  $p_{def} = 550 \text{ cm}^{-3} (\text{km s}^{-1})^2$ . The difference between these two galaxies is not the ram pressure they feel but the effect that that ram pressure has on their (current) HI disk.<sup>7</sup>

Following Köppen et al. (2018), we use the same  $\beta$  model of the cluster and associated parameters to estimate the ICM density and the cluster mass distribution. The velocities of the galaxies at a given radius, still following Köppen et al. (2018), are estimated as being the local escape velocity, derived using the  $\beta$  model for the cluster mass distribution. From this, we calculate the local ram pressure for those galaxies in our sample at the 17 Mpc distance of the main cluster (where the  $\beta$  model is applicable), assuming an average deprojected distance from the cluster center of  $\sqrt{4/3}$  times their projected distance from the cluster center (i.e., spherical symmetry). The results are plotted in Figure 7, which shows  $[C II]/TIR$  versus the local

<sup>7</sup> The situation may well be different where ram-pressure stripping and shocks are observed to be affecting the molecular gas disk (e.g., Jáchym et al. (2019); Moretti et al. (2020); Cramer et al. (2020)), as the  $[C II]$  and the molecular gas are likely to have similar extents (e.g., de Blok et al. (2016); Bigiel et al. (2020)). However, such observations are currently only available for a few galaxies so do not lend themselves to inclusion in this kind of analysis.



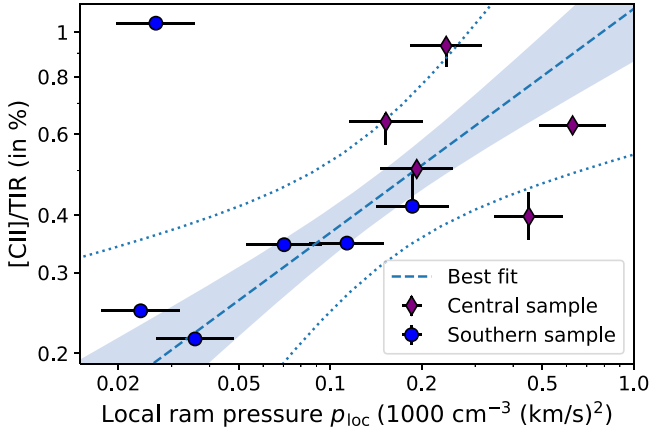
**Figure 6.**  $[C II]/TIR$  vs.  $p_{loc}/p_{def}$  with ram-pressure stripping category (both from Köppen et al. 2018) for our central galaxies (purple lozenges) and southern galaxies (blue circles). Magenta squares with colored error bars indicate the mean of each category (errors on the means, as before, estimated by propagating the errors on the individual measurements in the samples and combining these in quadrature with the uncertainty in the estimates of the means due to the scatter in the samples) and the dashed magenta line indicates where Köppen et al. (2018) split their categories. VCC 699, which has  $p_{loc}/p_{def} = 0$  in Köppen et al. (2018), is artificially placed at  $p_{loc}/p_{def} = 0.025$  with an arrow to the left.

ram pressure. The error bars on  $p_{loc}$  indicate fractional differences in the cluster-centric distances of  $\sqrt{4/3} - 1$ , i.e., the difference between the uncorrected and deprojected cluster-centric distances.

If the outlier VCC 737 (top left of Figure 7) is excluded, we find a Spearman’s  $\rho = 0.75$  which, with 10 pairs, gives a significance of  $p = 0.013$ , indicating that there is likely to be a correlation between  $[C II]/TIR$  and the local ram pressure. We fit this correlation with a power-law model as  $\log([C II]/TIR) = (0.49 \pm 0.13) \times \log(p_{loc}) + (0.05 \pm 0.12)$ , where  $[C II]/TIR$  is given as a percentage and  $p_{loc}$  in units of  $1000 \text{ cm}^{-3} (\text{km/s})^2$ . The local ram pressure calculated here could be affected by projection effects, where the three-dimensional position of a source lies in front of or behind the plane of the cluster center, result in the projected distance to the cluster center being lower than the actual three-dimensional distance. As the ram pressure a galaxy feels is due to its actual distance from the cluster center but our calculation here is based on their projected distance, our estimates of the ram pressure will be high for galaxies that are projected onto the cluster center, moving them to the right on Figure 7. This provides a possible explanation for why VCC 562 falls clearly (including the uncertainties on its measurement) outside of the  $3\sigma$  scatter around the best-fit line: it may lie either in front of or behind the cluster rather than near where it is seen in projection, so that its local ram pressure is lower than that calculated based on projected separation from the cluster center.

The correlation we see in Figure 7 is unexpectedly strong, continuing as it does into the outer parts of the cluster where  $[C II]/TIR$  is similar to that seen in our control sample from the DGS, which was expected to be free of environmental effects (although we do not know the local environments of the DGS galaxies), implying that ram pressure could have an effect on  $[C II]/TIR$  well outside the central region of the cluster and possibly even in galaxy groups (see Roberts et al. 2021).





**Figure 7.**  $[\text{C II}]/\text{TIR}$  vs. local ram pressure ( $p_{\text{loc}}$ ) calculated as in Equation (1) for our central galaxies (purple lozenges) and southern galaxies (blue circles) at 17 Mpc distance. Dashed line indicates best fit, the shaded area the  $1\sigma$  uncertainty, and the dotted line the  $3\sigma$  uncertainty.

Our finding that the central sample galaxies are more likely to have high values of  $[\text{C II}]/\text{TIR}$  than those in the southern sample thus appears to be linked to the higher values of  $p_{\text{loc}}$  felt by the central sample, i.e., their ram-pressure interaction with the ICM, without being necessarily linked to whether they are actively undergoing ram-pressure stripping of their gas. It seems likely, therefore, that the excess we see in  $[\text{C II}]/\text{TIR}$  is due to  $[\text{C II}]$  formation in shocks in the ISM of these galaxies caused by the ram pressure they are feeling.

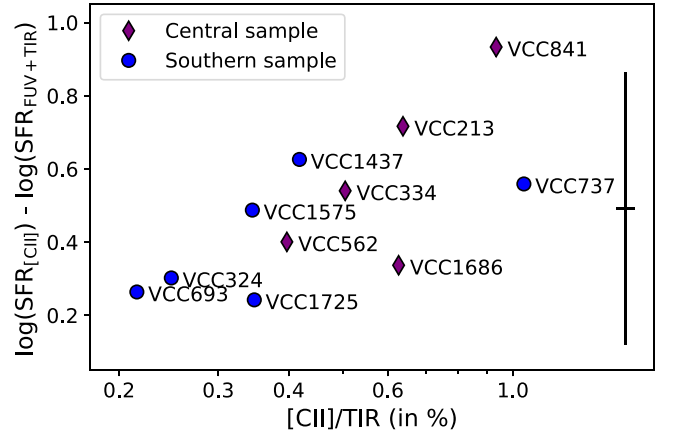
### 3.3. Comparison of Star-formation Rate Indicators

We use the calibration of Hao et al. (2011) to derive a star-formation rate (SFR) from the GALEX far ultraviolet (FUV) luminosities combined with our TIR luminosities. We also use the  $[\text{C II}]$  calibration of De Looze et al. (2014) for low-metallicity dwarfs to derive an SFR from the  $[\text{C II}]$  luminosities. This gives us a measure of excess  $[\text{C II}]$  based on star formation,  $\text{SFR}_{[\text{C II}]} / \text{SFR}_{\text{FUV}+\text{TIR}}$ .<sup>8</sup>

In Figure 8, we plot this against  $[\text{C II}]/\text{TIR}$  for the dwarf galaxies in the main cluster. It can be seen that this shows an increase in  $[\text{C II}]$  excess measures via SFR indicators as  $[\text{C II}]/\text{TIR}$  increases, as expected if the  $[\text{C II}]/\text{TIR}$  increase is due to the creation of  $[\text{C II}]$  via processes other than star formation. If, on the other hand, the excess in  $[\text{C II}]/\text{TIR}$  was caused by a rise in unobscured star formation, i.e., the  $[\text{C II}]$  seen here is being created by star formation that is not reflected in the TIR emission, we would not expect to see any increase in  $\text{SFR}_{[\text{C II}]} / \text{SFR}_{\text{FUV}+\text{TIR}}$ . Two galaxies fall below this trend: VCC 737, already identified as having an anomalously high value of  $[\text{C II}]/\text{TIR}$  for its position in the cluster, and VCC 1686 which, as described in Section 3.4.3 below, has strong UV emission that is not correlated spatially with either the  $[\text{C II}]$  or the dust and is probably due to recent star formation; this galaxy would thus be expected to show a deficit of  $[\text{C II}]$  relative to the FUV+TIR SFR, which translates into a deficit relative to the trend here.

The trend seen here is much tighter than the scatter on the SFR indicators (shown by the error bar on the right side of the plot), which is dominated by the scatter on the  $[\text{C II}]$ -SFR calibration. One possibility for our trend being tighter than the

<sup>8</sup> Both of these relationships are derived using a Kroupa & Weidner (2003) initial mass function.



**Figure 8.** Difference between SFR estimated from FUV+TIR and estimated from  $[\text{C II}]$ , plotted against  $[\text{C II}]/\text{TIR}$ . The error bar on the right-hand side indicates the scatter in the SFR indicators and the average error on  $[\text{C II}]/\text{TIR}$ ; vertical position of the error bar marks the average difference between the SFR indicators.

scatter is the relatively narrow range of luminosities and metallicities covered by our sample, while another is that De Looze et al. (2014) use the  $24 \mu\text{m}$  flux as a proxy for the total infrared flux in their measurement of SFR that they compare to the  $[\text{C II}]$ , whereas we measure TIR based on the whole SED here.

As can be seen in Figure 8, the SFR calibrations used give an excess of  $[\text{C II}]$  for all of the galaxies in our sample, although, for four of the 11 galaxies, this is within the  $1\sigma$  scatter around zero and, for all but VCC 841, it is within the  $2\sigma$  scatter. However, applying the  $[\text{C II}]$ -SFR calibration of Herrera-Camus et al. (2015) gives (after correcting the SFR from the Salpeter (1955) initial mass function used by Herrera-Camus et al. (2015) to the Kroupa & Weidner (2003) initial mass function used by De Looze et al. (2014) and Hao et al. (2011) using the ratio of 0.67 found by Madau & Dickinson (2014)) a similar shape while showing a deficit of  $\text{SFR}_{[\text{C II}]} / \text{SFR}_{\text{FUV}+\text{TIR}}$  for all but four galaxies in the sample. Thus this appears to be an issue of calibration of the zero point, which is of secondary importance for the relationship being examined here: the clear increase in  $\text{SFR}_{[\text{C II}]} / \text{SFR}_{\text{FUV}+\text{TIR}}$  with increasing  $[\text{C II}]/\text{TIR}$ .

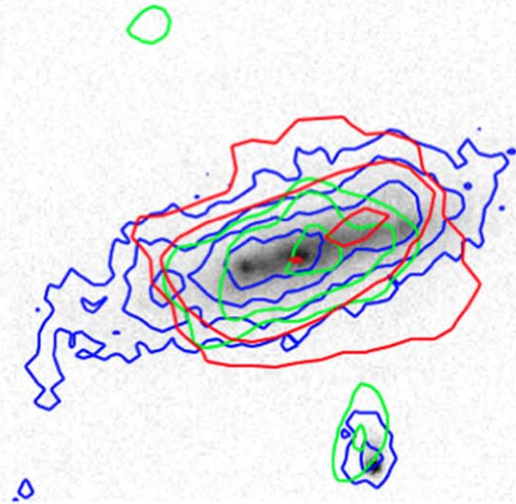
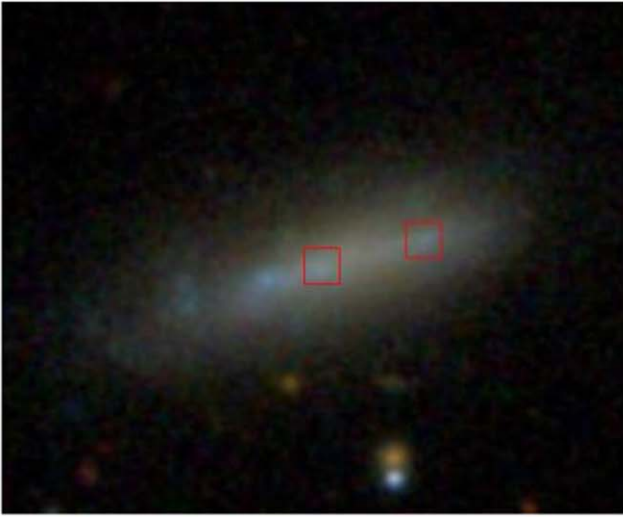
### 3.4. Notes on Individual Galaxies

We present here notes on three of the galaxies with the highest  $[\text{C II}]/\text{TIR}$  in our sample: VCC 737, VCC 841, and VCC 1686. Two of these are in the central region of the cluster, while the third (VCC 737) is on the cluster outskirts and appears anomalous in terms of its  $[\text{C II}]/\text{TIR}$  compared to its cluster position.

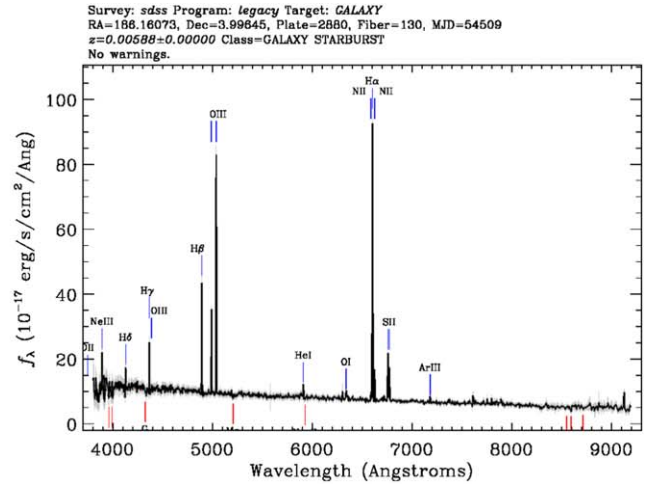
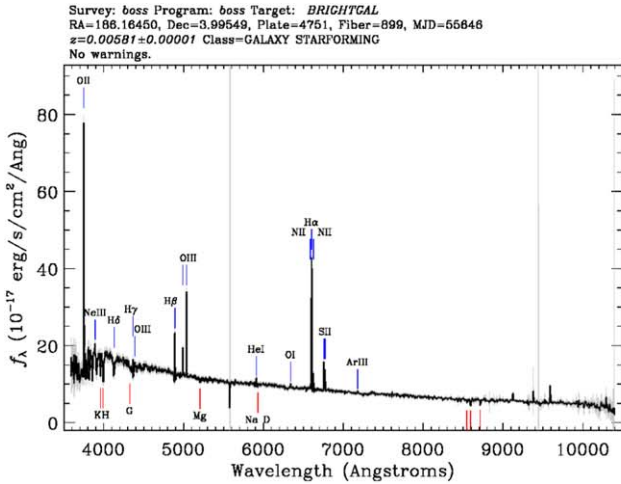
#### 3.4.1. VCC 737

VCC 737 is far from the cluster core, at a projected distance of 2.5 Mpc, and is estimated to have a low local ram pressure, but has the highest  $[\text{C II}]/\text{TIR}$  in our sample, making it an outlier in these relationships.

Figure 9 shows the SDSS (York et al. 2000) color image of VCC 737 from Data Release 13 (Albaret et al. 2017) and contour maps of the  $[\text{C II}]$ , mid-IR and near-UV regions. There are two SDSS spectra on this galaxy, shown in Figure 10. The eastern part of this galaxy, including the location of the central



**Figure 9.** VCC 737 optical color image from the SDSS (left) with north up and east to the left; and SDSS  $g$ -band image overlaid with [C II] (R), WISE band 3 (G), and GALEX NUV (B) contours (right) at levels of  $2.5, 5,$  and  $10 \times 10^{-19} \text{ W m}^{-2} \text{ spaxel}^{-1}$  (4.4, 8.8 and  $18\sigma$ ) for the [C II]; 2, 2.8, and 4 DN  $\text{pixel}^{-1}$  (3.5, 4.9 and  $7.0\sigma$ ) above the sky value of  $776.5 \text{ DN pixel}^{-1}$  for WISE band 3; and 0.0125, 0.025, 0.05, and 0.1 counts  $\text{s}^{-1} \text{ pixel}^{-1}$  ( $6.0, 12, 24$  and  $48\sigma$ ) for the GALEX NUV. The locations of the SDSS spectrum (Figure 10) are marked with red boxes on the SDSS color image.



**Figure 10.** SDSS preview spectra of VCC 737 central region (left) and western region (right). Red and blue labels indicate automatically identified absorption and emission features; gray band indicates uncertainty in the flux.

spectrum, contains coincident peaks in [C II], dust, and UV. However, the western part has a stronger [C II] peak that is not matched by peaks in either dust or UV, giving it a clear excess of [C II]. The western SDSS spectrum shows a much stronger  $H\alpha$  line than the central spectrum (a flux of  $615.8 \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1}$  in the SDSS catalog versus  $200 \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1}$  for the central region),<sup>9</sup> and the  $H\alpha/H\beta$  ratios of 3.6 for the western region and 3.4 for the central region (again from the SDSS catalog) imply that the two regions have similar internal absorption. However, although there is a local peak in the near-UV emission near the location of the western spectrum, it is around half the strength of the near-UV emission in the central region: the local UV peaks at  $0.088 \text{ cnt s}^{-1} \text{ pix}^{-1}$  in the pixel on the northern edge of the western SDSS spectrum versus  $0.164 \text{ cnt s}^{-1} \text{ pix}^{-1}$  in the central pixel of the central SDSS spectrum. The eastern UV

(which does not have an associated SDSS spectrum, but corresponds to the bluer eastern region in the SDSS image) peaks at  $0.163 \text{ cnt s}^{-1} \text{ pix}^{-1}$ .

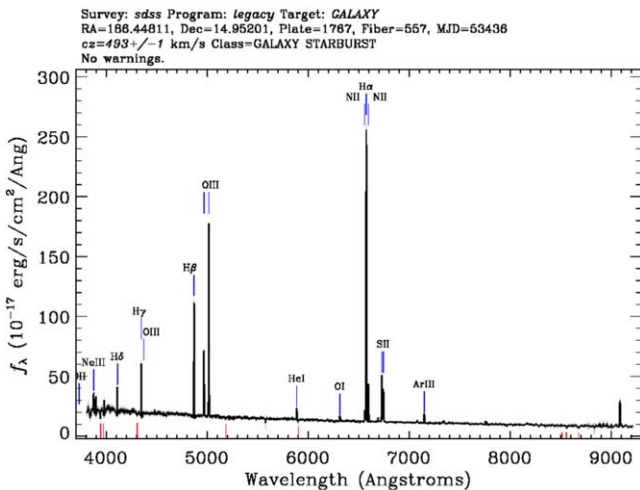
This pattern of [C II] enhancement in an area with little warm dust emission is quite distinct from that expected from ram-pressure shocks, where triggered star formation is expected to occur in the shocks (e.g., Kapferer et al. 2009), producing enhanced dust, [C II], and UV from star formation alongside the additional [C II] that may be formed directly from the shock (as seen in VCC 841; Figure 11). Based on its optical diameters in GOLDMine (Gavazzi et al. 2014) and its HI mass from ALFALFA (Haynes et al. 2018), we estimate an HI deficiency (Haynes & Giovanelli 1984) of  $-0.17$  for VCC 737, within the range of normal (unstripped) galaxies.

Clearly, the high [C II]/TIR measured in VCC 737 is due to the [C II] peak in the western part of this galaxy, but exploring the details of what might be exciting strong [C II] and  $H\alpha$  emission without the expected enhancement in the dust luminosity or UV in this galaxy is beyond the scope of this paper.

<sup>9</sup> See catalog entries at <https://dr12.sdss.org/spectrumDetail?mjd=54509&fiber=130&plateid=2880> and <https://dr12.sdss.org/spectrumDetail?mjd=55646&fiber=899&plateid=4751>.



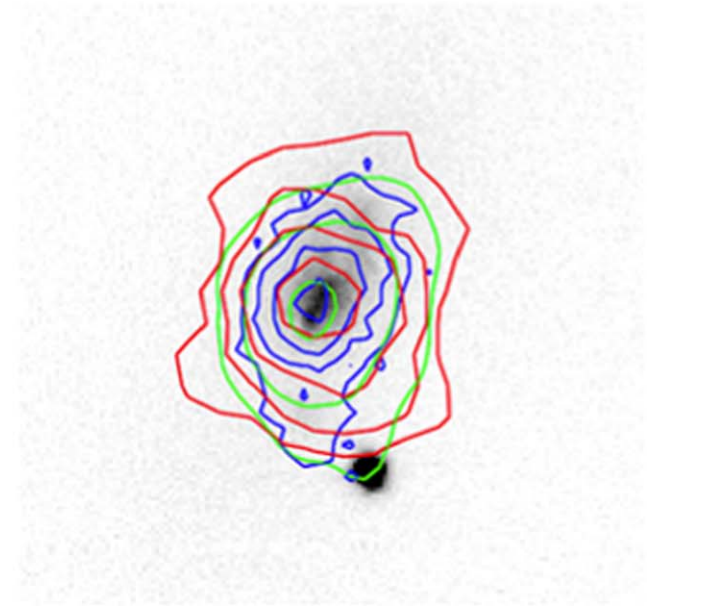
**Figure 11.** VCC 841 optical color image from the SDSS (left) with north up and east to the left; and SDSS g-band image overlaid with [C II] (R), WISE band 3 (G), and GALEX NUV (B) contours (right) at levels of 2.5, 5, 10, and  $20 \times 10^{-19} \text{ W m}^{-2} \text{ spaxel}^{-1}$  (4.5, 9, 18 and  $36\sigma$ ) for the [C II]; 2.5, 5, and 10 DN pixel $^{-1}$  (6.0, 12 and  $23\sigma$ ) above the sky value of 604 DN pixel $^{-1}$  for WISE band 3; and 0.0125, 0.025, 0.05, and 0.1 counts s $^{-1}$  pixel $^{-1}$  (5.6, 11, 22 and  $44\sigma$ ) for the GALEX NUV. The location of the SDSS spectrum (Figure 12) is marked with a red box on the SDSS color image.



**Figure 12.** SDSS spectrum of VCC 841. Red and blue labels indicate automatically identified absorption and emission features; gray band indicates uncertainty in the flux.

### 3.4.2. VCC 841

Figure 11 shows the SDSS color image of VCC 841 and contour maps of the [C II], mid-IR, and near-UV. The SDSS image shows an off-center nucleus, which is coincident with the [C II], dust, and UV centers, with the rest of the galaxy to the northwest of this nucleus. The SDSS spectrum of the nucleus (Figure 12) shows a strong H $\alpha$  line. Comparison with Figure 4 shows that the nucleus is on the side of the galaxy closest to M87. This is consistent with this galaxy undergoing ram-pressure effects that are triggering star formation in the nucleus, which would naturally be expected to enhance both [C II] and TIR, with the excess [C II]/TIR being due to ram-pressure shocks. It is not listed in Köppen et al. (2018), but based on its optical diameters in GOLDMine and its H I mass



from ALFALFA we estimate an H I deficiency of 0.67, consistent with it being ram-pressure stripped.

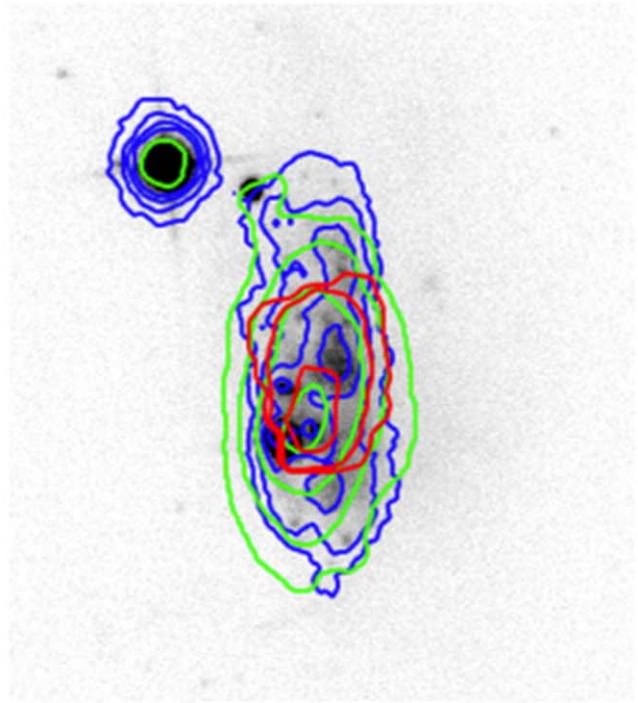
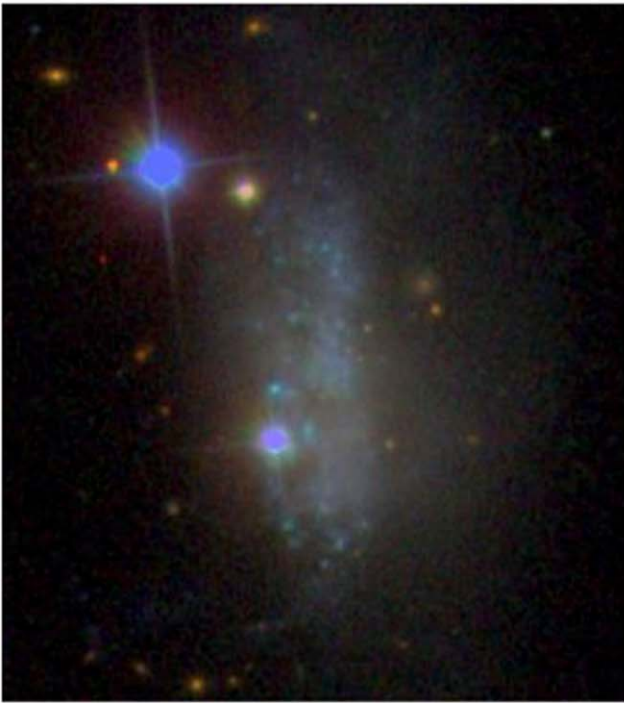
### 3.4.3. VCC 1686

Figure 13 shows the SDSS color image of VCC 1686 and contour maps of the [C II], mid-IR, and near-UV regions. The [C II] and dust are well aligned, with the UV being enhanced in the areas to the northwest of the galaxy that also show very blue colors in the SDSS image and are probably the site of recent star formation as there is no dust or [C II] enhancement seen in this region. It is also likely that some [C II] flux is lost off the edge of the PACS footprint. This galaxy is considered an “active stripper” by Köppen et al. (2018), who calculate that it has an H I deficiency of 0.45. Based on its optical diameters in GOLDMine and an updated H I mass from ALFALFA, we estimate a slightly lower H I deficiency of 0.39, still consistent with it undergoing stripping.

## 4. Conclusions

In recent years, the consensus that [C II] has its origin in, and thus traces, star formation has been challenged by the discovery of [C II] formed from the interactions of AGN jets with the disk (Appleton et al. 2018; Smirnova-Pinchukova et al. 2019; Fadda et al. 2021) and in galaxy-galaxy interactions (Appleton et al. 2013, 2017; Peterson et al. 2018). To these, as suggested by Pierini et al. (1999), we can now add the interaction of galaxies with the cluster environment. The most likely source of the [C II]/TIR excess observed in our sample in galaxies near the cluster core is the formation of [C II] in ram-pressure shocks.

The dwarf galaxies studied here in the central part of the Virgo cluster have significantly higher average ratios of [C II] to total infrared continuum than the dwarf galaxies in the southern part of the Virgo cluster ( $p = 0.086$ ), with  $\langle [\text{C II}]/\text{TIR} \rangle = 0.62 \pm 0.09$  in the center and  $\langle [\text{C II}]/\text{TIR} \rangle = 0.45 \pm 0.08$  in the south for a  $1.4\sigma$  difference. After controlling for metallicity and luminosity, the



**Figure 13.** VCC 1686 optical color image from the SDSS (left) with north up and east to the left; and SDSS g-band image overlaid with [C II] (R), WISE band 3 (G), and GALEX NUV (B) contours (right) at levels of 1, 2, and  $4 \times 10^{-18} \text{ W m}^{-2} \text{ spaxel}^{-1}$  (9.8, 19.5 and  $39.0\sigma$ ) for the [C II]; 2.5, 5, 10, and 20 DN pixel $^{-1}$  (6.3, 13, 25, and  $51\sigma$ ) above the sky value of 647 DN pixel $^{-1}$  for WISE band 3; and 0.025, 0.05, 0.1, and 0.2 counts s $^{-1}$  pixel $^{-1}$  (7.6, 15, 30 and  $61\sigma$ ) for the GALEX NUV.

southern sample is consistent with the Herschel Dwarf Galaxy Survey (DGS) while the central sample shows a significant difference ( $p = 0.040$ ), with the DGS subsample having  $\langle [\text{C II}]/\text{TIR} \rangle = 0.37 \pm 0.05$  for a  $2.4\sigma$  difference. This implies the existence of processes in the cluster environment that are injecting energy into the interstellar medium of these galaxies. The most likely candidate for such a process is an interaction between the interstellar medium of these galaxies and the intra-cluster medium, i.e., ram pressure. However, as ram-pressure stripping is a combination of both the local ram pressure felt by the galaxy and how tightly bound the H I is to that galaxy, galaxies that are tightly bound (or already partially stripped) near cluster cores may suffer ram-pressure shocks to their ISM, leading to the formation of [C II], without exhibiting signs of current ram-pressure stripping. Similarly, galaxies that are loosely bound further from cluster cores may be undergoing stripping without showing a [C II] excess. When we look at just the local ram pressure, we find a correlation between this and [C II]/TIR that can be fitted as a power-law model with a slope of  $0.49 \pm 0.13$ .

While the effect detected here as a difference between the central and southern galaxies and as a correlation between the ratio of [C II] to total infrared continuum and the local ram pressure is statistically significant, increasing the number of data points would increase confidence in this result. In order to improve our understanding of the effect of ram-pressure shocks on [C II] in cluster galaxies, and whether it is indeed ram pressure that is responsible for the observed [C II] excess, further studies will be necessary. Comparison of galaxies near the centers of galaxy clusters with suitable control samples, as done in this study, is one way forward, but other possibilities include observations of larger galaxies where the shocked regions can be identified and compared with unshocked regions (particularly where the shocks are clearly affecting the molecular gas) and observations of galaxies in clusters, such

as Coma, that have a stronger ram-pressure effect than Virgo. NASA's Stratospheric Observatory for Infrared Astronomy and future proposed observatories such as the Origins Space Telescope will be vital for this effort to comprehend the origins of [C II] in our local universe and thus better understand observations of the high-redshift universe.

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*Facilities:* IRSA, WISE, Herschel, GALEX.

*Software:* Astropy (Astropy Collaboration et al. 2013, 2018), NumPy (Harris et al. 2020), SAOImageDS9 (Joye & Mandel 2003), SOSPEX (Fadda & Chambers 2018), Web-PlotDigitizer (<https://apps.automeris.io/wpd/>).

## Appendix Input Fluxes for the SED Fitting

The input fluxes for the SED fitting (Section 2.2) are given in Table A1.


**Table A1**  
Input Fluxes for The SED Fitting (Jy)

Galaxy ID	GALEX FUV (0.15 $\mu\text{m}$ ) SDSS <i>r</i> (0.62 $\mu\text{m}$ ) 2MASS <i>H</i> (1.7 $\mu\text{m}$ ) WISE B3 (12 $\mu\text{m}$ ) PACS 250 (250 $\mu\text{m}$ )	GALEX NUV (0.23 $\mu\text{m}$ ) SDSS <i>i</i> (0.75 $\mu\text{m}$ ) 2MASS <i>K<sub>s</sub></i> (2.2 $\mu\text{m}$ ) WISE B4 (23 $\mu\text{m}$ ) SPIRE 350 (350 $\mu\text{m}$ )	SDSS <i>u</i> (0.36 $\mu\text{m}$ ) SDSS <i>z</i> (0.90 $\mu\text{m}$ ) WISE B1 (3.4 $\mu\text{m}$ ) PACS 100 (100 $\mu\text{m}$ ) SPIRE 500 (500 $\mu\text{m}$ )	SDSS <i>g</i> (0.47 $\mu\text{m}$ ) 2MASS <i>J</i> (1.2 $\mu\text{m}$ ) WISE B2 (4.6 $\mu\text{m}$ ) PACS 160 (160 $\mu\text{m}$ )
VCC 144	0.00147 ± 0.00007 0.00510 ± 0.00009 0.00648 ± 0.00067 0.0113 ± 0.0003 0.182 ± 0.016	0.00180 ± 0.00005 0.00490 ± 0.00009 0.00466 ± 0.00083 0.0692 ± 0.0041 0.080 ± 0.010	0.00250 ± 0.00009 0.00510 ± 0.00015 0.00327 ± 0.00004 0.724 ± 0.052 0.036 ± 0.004	0.00431 ± 0.00008 0.00656 ± 0.00049 0.00204 ± 0.00006 0.525 ± 0.040
VCC 213	0.000581 ± 0.000074 0.0128 ± 0.0002 0.0278 ± 0.0011 0.0298 ± 0.0004 0.516 ± 0.038	0.00092 ± 0.00007 0.0166 ± 0.0003 0.0237 ± 0.0013 0.0381 ± 0.0035 0.257 ± 0.020	0.00272 ± 0.00010 0.0195 ± 0.0006 0.0116 ± 0.0001 1.130 ± 0.063 0.093 ± 0.004	0.00787 ± 0.00014 0.0265 ± 0.0008 0.00681 ± 0.00007 1.135 ± 0.064
VCC 324	0.00127 ± 0.00006 0.0120 ± 0.0002 0.0149 ± 0.0012 0.0201 ± 0.0006 0.318 ± 0.024	0.00179 ± 0.00006 0.0135 ± 0.0002 0.0114 ± 0.0011 0.104 ± 0.004 0.153 ± 0.014	0.00392 ± 0.00014 0.0164 ± 0.0005 0.00595 ± 0.00006 0.965 ± 0.061 0.086 ± 0.004	0.00874 ± 0.00016 0.0143 ± 0.0007 0.00380 ± 0.00006 0.717 ± 0.058
VCC 334	0.000355 ± 0.000064 0.00307 ± 0.00006 0.00406 ± 0.00075 0.00180 ± 0.00030 0.070 ± 0.009	0.000498 ± 0.000058 0.00377 ± 0.00007 0.00273 ± 0.00085 0.00334 ± 0.00109 0.029 ± 0.005	... ± ... 0.00412 ± 0.00012 0.00191 ± 0.00004 0.137 ± 0.022 ... ± ...	0.00229 ± 0.00004 0.00434 ± 0.00050 0.000997 ± 0.000047 0.163 ± 0.018
VCC 340	0.000635 ± 0.000056 0.00748 ± 0.00014 0.0141 ± 0.0010 0.00723 ± 0.00027 0.274 ± 0.018	0.000908 ± 0.000053 0.00915 ± 0.00017 0.00870 ± 0.00089 0.0284 ± 0.0060 0.120 ± 0.011	0.00209 ± 0.00007 0.0109 ± 0.0003 0.00528 ± 0.00005 0.455 ± 0.037 0.058 ± 0.004	0.00525 ± 0.00010 0.0106 ± 0.0006 0.00313 ± 0.00006 0.394 ± 0.047
VCC 562	0.000484 ± 0.000043 0.00195 ± 0.00004 0.00146 ± 0.00083 0.00177 ± 0.00032 0.059 ± 0.006	0.000667 ± 0.000047 0.00207 ± 0.00004 0.00175 ± 0.00070 0.0115 ± 0.0040 0.045 ± 0.005	0.000823 ± 0.000029 0.00287 ± 0.00009 0.00162 ± 0.00003 0.133 ± 0.021 0.032 ± 0.004	0.00154 ± 0.00003 0.00311 ± 0.00045 0.000936 ± 0.000046 0.125 ± 0.015
VCC 693	0.000584 ± 0.000080 0.00714 ± 0.00013 0.00467 ± 0.00099 0.00293 ± 0.00036 0.153 ± 0.014	0.000882 ± 0.000079 0.00826 ± 0.00015 0.00630 ± 0.00151 ... ± ... 0.075 ± 0.009	0.00208 ± 0.00007 0.00742 ± 0.00021 0.00257 ± 0.00004 0.134 ± 0.025 0.030 ± 0.004	0.00539 ± 0.00010 0.00675 ± 0.00086 0.00144 ± 0.00007 0.219 ± 0.039
VCC 699	0.00269 ± 0.00010 0.0218 ± 0.0004 0.0218 ± 0.0012 0.0217 ± 0.00062 0.722 ± 0.054	0.00400 ± 0.00009 0.0264 ± 0.0005 0.0199 ± 0.0014 0.0519 ± 0.0040 0.361 ± 0.030	0.00708 ± 0.00024 0.0256 ± 0.0007 0.0120 ± 0.0001 1.427 ± 0.102 0.146 ± 0.016	0.0157 ± 0.0003 0.0223 ± 0.0009 0.00688 ± 0.00007 1.398 ± 0.087
VCC 737	0.000593 ± 0.000107 0.00587 ± 0.00011 0.00784 ± 0.00112 0.00293 ± 0.00038 0.150 ± 0.013	0.000841 ± 0.000092 0.00656 ± 0.00012 0.00893 ± 0.00154 ... ± ... 0.093 ± 0.008	0.00167 ± 0.00006 0.00906 ± 0.00026 0.00323 ± 0.00004 0.109 ± 0.019 0.049 ± 0.004	0.00401 ± 0.00007 0.00679 ± 0.00089 0.00180 ± 0.00005 0.157 ± 0.019
VCC 841	0.000136 ± 0.000067 0.00460 ± 0.00009 0.00602 ± 0.00106 0.00418 ± 0.00032 0.101 ± 0.011	0.000248 ± 0.000051 0.00591 ± 0.00011 0.00686 ± 0.00094 0.0123 ± 0.0033 0.042 ± 0.007	0.00105 ± 0.00004 0.00762 ± 0.00022 0.00487 ± 0.00004 0.138 ± 0.025 0.011 ± 0.003	0.00283 ± 0.00005 0.00554 ± 0.00062 0.00263 ± 0.00007 0.156 ± 0.017
VCC 1437	0.000291 ± 0.000040 0.00613 ± 0.00011 0.0125 ± 0.0012 0.0117 ± 0.0004 0.176 ± 0.017	0.000467 ± 0.000049 0.00785 ± 0.00015 0.00825 ± 0.00110 0.0288 ± 0.0049 0.065 ± 0.010	0.00142 ± 0.00005 0.00917 ± 0.00026 0.00532 ± 0.00004 0.454 ± 0.037 0.034 ± 0.004	0.00404 ± 0.00007 0.0104 ± 0.0007 0.00301 ± 0.00006 0.434 ± 0.045
VCC 1575	0.000822 ± 0.000049 0.0276 ± 0.0005 0.0550 ± 0.0026 0.0475 ± 0.0004 1.292 ± 0.094	0.00145 ± 0.00006 0.0359 ± 0.0007 0.0506 ± 0.0026 0.136 ± 0.006 0.542 ± 0.041	0.00484 ± 0.00017 0.0436 ± 0.0012 0.0175 ± 0.0001 2.319 ± 0.141 0.186 ± 0.016	0.0159 ± 0.0003 0.0472 ± 0.0016 0.0105 ± 0.0001 2.706 ± 0.142

**Table A1**  
(Continued)

Galaxy ID	GALEX FUV (0.15 $\mu\text{m}$ ) SDSS <i>r</i> (0.62 $\mu\text{m}$ ) 2MASS <i>H</i> (1.7 $\mu\text{m}$ ) WISE B3 (12 $\mu\text{m}$ ) PACS 250 (250 $\mu\text{m}$ )	GALEX NUV (0.23 $\mu\text{m}$ ) SDSS <i>i</i> (0.75 $\mu\text{m}$ ) 2MASS <i>K<sub>S</sub></i> (2.2 $\mu\text{m}$ ) WISE B4 (23 $\mu\text{m}$ ) SPIRE 350 (350 $\mu\text{m}$ )	SDSS <i>u</i> (0.36 $\mu\text{m}$ ) SDSS <i>z</i> (0.90 $\mu\text{m}$ ) WISE B1 (3.4 $\mu\text{m}$ ) PACS 100 (100 $\mu\text{m}$ ) SPIRE 500 (500 $\mu\text{m}$ )	SDSS <i>g</i> (0.47 $\mu\text{m}$ ) 2MASS <i>J</i> (1.2 $\mu\text{m}$ ) WISE B2 (4.6 $\mu\text{m}$ ) PACS 160 (160 $\mu\text{m}$ )
VCC 1686	0.00303 $\pm$ 0.00008 0.0123 $\pm$ 0.0002 0.0259 $\pm$ 0.0018 0.0205 $\pm$ 0.0005 1.13 $\pm$ 0.106	0.00435 $\pm$ 0.00009 0.0207 $\pm$ 0.0004 0.0239 $\pm$ 0.0015 0.0334 $\pm$ 0.0015 0.621 $\pm$ 0.063	0.00550 $\pm$ 0.00019 0.0219 $\pm$ 0.0006 0.0133 $\pm$ 0.0002 1.061 $\pm$ 0.08 0.232 $\pm$ 0.026	0.0168 $\pm$ 0.0003 0.0256 $\pm$ 0.0010 0.00798 $\pm$ 0.00015 1.714 $\pm$ 0.105
VCC 1725	0.00169 $\pm$ 0.00005 0.00993 $\pm$ 0.00018 0.00929 $\pm$ 0.00157 0.00461 $\pm$ 0.00029 0.287 $\pm$ 0.025	0.00205 $\pm$ 0.00006 0.0116 $\pm$ 0.0002 0.0098 $\pm$ 0.0016 ... $\pm$ ... 0.172 $\pm$ 0.016	0.00295 $\pm$ 0.00010 0.0108 $\pm$ 0.0003 0.00385 $\pm$ 0.00005 0.357 $\pm$ 0.033 0.082 $\pm$ 0.009	0.00788 $\pm$ 0.00015 0.00801 $\pm$ 0.00093 0.00223 $\pm$ 0.00007 0.377 $\pm$ 0.034

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