A MULTI-WAVELENGTH STUDY OF LOW-REDSHIFT CLUSTERS OF GALAXIES. II.
ENVIRONMENTAL IMPACT ON GALAXY GROWTH

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ABSTRACT

Galaxy clusters provide powerful laboratories for the study of galaxy evolution, particularly the origin of correlations of morphology and star formation rate (SFR) with density. We construct visible to MIR spectral energy distributions of galaxies in eight low-redshift ($z < 0.3$) clusters and use them to measure stellar masses and SFRs as a function of environment. A partial correlation analysis indicates that the SFRs of star-forming galaxies (SFGs) depend strongly on $M_*$ ($>99\%$ confidence) with no dependence on $R/R_{200}$ or projected local density at fixed mass. A merged sample of galaxies from the five best measured clusters shows $\langle SFR \rangle \propto (R/R_{200})^{1.1 \pm 0.3}$ for galaxies with $R/R_{200} \leq 0.4$. A decline in the fraction of SFGs toward the cluster center contributes most of this effect, but it is accompanied by a reduction in $\langle SFR \rangle$ for SFGs with $R \leq 0.1 R_{200}$. The increase in the fraction of SFGs toward larger $R/R_{200}$ and the isolation of SFGs with reduced SFRs near the cluster center are consistent with the truncation of star formation by ram-pressure stripping, as is the tendency for more massive SFGs to have higher SFRs. We conclude that stripping is more likely than slower processes to drive the properties of SFGs with $R < 0.4 R_{200}$ in clusters. We also find that galaxies near the cluster center are more massive than galaxies farther out in the cluster at $\sim 3.5 \sigma$, which suggests that dynamical relaxation significantly impacts the distribution of cluster galaxies as the clusters evolve.

Key words: galaxies: clusters: general – galaxies: evolution – galaxies: star formation – infrared: galaxies

Online-only material: color figures, machine-readable tables

1. INTRODUCTION

The current paradigm for the evolution of the universe and the growth of structure is based largely on observations of the luminous matter in the universe, i.e., individual galaxies, groups, and clusters, and the cosmic microwave background. While galaxy formation physics could previously be neglected, the era of precision cosmology increasingly demands detailed knowledge of galaxy formation to map observations of luminous matter onto dark matter halos (e.g., van Daalen et al. 2011). To do so precisely, we must understand the relationship between galaxy evolution and environment.

Galaxy formation theory dates to the middle of the twentieth century. Early work explored the physical processes responsible for star formation (Whipple 1946), speculated about the origins of the Milky Way (Eggen et al. 1962), and examined the impact of environment on galaxy evolution (Spitzer & Baade 1951). Osterbrock (1960) discovered that star-forming galaxies (SFGs) are less common in galaxy clusters than in lower density environments, and this result was subsequently re-examined with larger samples (Gisler 1978; Dressler et al. 1985). The dearth of vigorous star formation in galaxy clusters is mirrored by an underabundance of spiral galaxies in these high-density regions, known as the morphology–density relation (Dressler 1980; Postman & Geller 1984; Dressler et al. 1997; Postman et al. 2005).

The impact of environment on the frequency and intensity of star formation has been studied intensely in galaxy clusters and also at a variety of other density scales. These measurements have employed both visible-wavelength colors (Kodama & Bower 2001; Balogh et al. 2004; Barkhouse et al. 2009; Hansen et al. 2009) and emission lines (Abraham et al. 1996; Balogh et al. 1997, 2000; Kauffmann et al. 2004; Christlein & Zabludoff 2005; Poggianti et al. 2006; Verdugo et al. 2008; Braglia et al. 2009; von der Linden et al. 2010) as well as mid-infrared (MIR) luminosities (Bai et al. 2006, 2009; Saintonge et al. 2008). SFGs are consistently found to be more common and to have higher star formation rates (SFRs) in lower density environments and at higher redshifts (Kauffmann et al. 2004; Poggianti et al. 2006, 2008). This trend begins to reverse at $z \approx 1$, where average SFRs are higher in intermediate- than low-density environments (Elbaz et al. 2007; Cooper et al. 2008). The reversal extends to clusters by $z \approx 2$ (Tran et al. 2010; Hatch et al. 2011). However, even high-$z$ cluster galaxies form their stars earlier than coeval field galaxies of similar mass (Rettura et al. 2011).

The relationships between SFR, morphology, and environment in the local universe place strong constraints on models for galaxy evolution. Another important factor is the presence of an evolutionary trend for galaxies to have higher SFRs at higher redshifts. This was originally reported as an excess of blue cluster members at $z \approx 0.4$ compared to $z = 0$ (Oemler 1974; Butcher & Oemler 1978, 1984), and is commonly known at the Butcher–Oemler effect. This trend is now understood to track the simultaneous increase in the fraction of SFGs and in the SFRs of individual SFGs. An analogous trend has been examined in the MIR (Saintonge et al. 2008; Haines et al. 2009; Tran et al. 2010; Hatch et al. 2011), which is sensitive to dust-enshrouded star formation.

The observed trends in star formation with environment and the variation of these trends with redshift are usually attributed to changes in the sizes of cold gas reservoirs. Several mechanisms have been proposed to reduce galaxies’ cold gas supplies and transform them from SFGs to passive galaxies. These mechanisms include ram-pressure stripping (RPS) of cold gas (Gunn & Gott 1972; Abadi et al. 1999; Quilis et al. 2012).
In this paper, we will employ this method to correct for AGNs and measure star formation in cluster galaxies. We use the results to study the relationship between star formation and the cluster environment. In particular, we consider the constraints placed on the important environmental processes that operate in clusters by the distribution of star formation among cluster members.

The paper is organized as follows. In Section 2, we review our observations, which are discussed in more detail in Paper I. In Section 3 we review the mathematical formalism associated with partial correlation analysis. In Section 4 we derive completeness corrections for the observed cluster members. We discuss the derivation of total infrared (TIR) LFs in Section 5, and in Section 6 we detail the results of our measurements. Finally, we examine the implications of these results for the environmental dependence of galaxy evolution in Section 7, and we summarize these conclusions in Section 8. Throughout this paper we adopt the WMAP 5-year cosmology—a Λ-CDM universe with \( \Omega_m = 0.26, \Omega_\Lambda = 0.74, \) and \( h = 0.72 \) (Dunkley et al. 2009).

2. OBSERVATIONS AND MEMBER DESCRIPTION

Paper I provides details of our photometry and spectroscopy. It also develops methods to reliably identify low-luminosity AGNs and to measure galaxy properties like stellar mass and SFRs for identified cluster members, including AGN hosts. We briefly summarize the salient points below.

2.1. Observations

We identified cluster member galaxies using redshifts determined by Martini et al. (2007). We supplemented these with redshifts from the literature, which we obtained from the NASA Extragalactic Database (NED).2 (These redshifts come from a variety of sources with unknown selection functions and success rates. See Section 4.)

We have visible-wavelength images from the du Pont telescope at Las Campanas observatory, MIR images from the IRAC and MIPS instruments on the Spitzer Space Telescope, and X-ray images extracted from the Chandra archive. We measure visible, MIR, and X-ray fluxes in redshift-dependent photometric apertures that approximate a fixed metric size. The aperture fluxes are then corrected to total fluxes at constant color with the R-band Kron-like magnitude from SExtractor (Bertin & Arnouts 1996). Our photometry spans the peak of the stellar continuum, so we have robust photometric redshifts, which can identify catastrophic errors among the spectroscopic redshifts. We find 12 such catastrophic errors, one of which is an AGN (Paper I). We exclude these objects from our analysis.

2.2. Cluster Member Description and AGN Identification

In Paper I, we constructed SEDs from the photometry described in Section 2.1, and we fitted models to these fluxes with SED template codes from Assel et al. (2010). We used these model SEDs to derive photometric redshifts and K-corrections. We also employed the models to measure MIR color corrections, which we needed to determine rest-frame luminosities.

We employ rest-frame, visible-wavelength colors to determine the mass-to-light ratio of each galaxy in the sample (Bell & de Jong 2001). We assume a scaled Salpeter initial mass function (IMF; Bell & de Jong 2001) to infer stellar masses from

2 http://nedwww.ipac.caltech.edu/
the combined mass-to-light ratios and the measured luminosities. We employ the relations determined by Zhu et al. (2008) to determine SFRs from the 8 μm and 24 μm luminosities separately. The Zhu et al. (2008) calibrations assume a Salpeter IMF, so we have multiplied the inferred SFRs by a factor of 0.7 to match the scaled Salpeter IMF we assumed to determine stellar masses. When SFRs can be measured in both bands, we take the geometric mean of the two measurements. We found in Paper I that SFRs determined independently from 8 μm and 24 μm luminosities show a scatter of ~0.2 dex with respect to one another. This scatter reflects the systematic uncertainty in SFR measurements determined from either band separately, and the applied systematic uncertainty is comparable to the systematic uncertainties in the measured stellar masses (0.3 dex, Paper I).

Before we measure stellar masses and SFRs of cluster members, we identify and correct for AGNs. We employ two independent methods to identify AGNs: the shapes of the model SEDs (IR AGNs) and the X-ray luminosities measured with Chandra (X-ray AGNs). The hosts of IR AGNs are corrected for the presence of the AGN before we calculate $M_*$ and SFR. X-ray AGNs without measurable signatures in their SEDs do not contribute significantly to the measured visible and MIR fluxes, so we do not correct those objects. In Paper I we found that the IR and X-ray AGN samples are largely disjoint. This implies that X-ray-only AGN selection can overlook a large fraction (~35%) of AGNs. We explore the potential consequences of this bias in Sections 6.5 and 6.6.

3. PARTIAL CORRELATION ANALYSIS

In a system of mutually correlated observables, it can be difficult to establish which variables drive the correlations. Partial correlation analysis measures the relationship between two variables with all other parameters held fixed and can identify which variable(s) control the observed correlations. Partial correlation analysis has been applied in the past to develop a fundamental plane of black hole activity (Merloni et al. 2003) and to probe the dependence of SFR on both stellar mass and environment simultaneously (Christlein & Zabludoff 2005). We will use the simplest formulation of partial correlation analysis, which relies only on direct measurements and does not account for upper limits.

The simplest case is a system of only three variables, $x_i$. This is called the first-order partial correlation problem. The correlation coefficient for $x_1$ and $x_2$ at fixed $x_3$ can be expressed as

$$r_{12|3} = \frac{\rho_{12} - \rho_{13}\rho_{23}}{\sqrt{1 - \rho_{13}^2}(1 - \rho_{23}^2)},$$

where $\rho_{ij}$ is the standard two-variable correlation coefficient (e.g., the Pearson or Spearman coefficients) between $x_i$ and $x_j$ (Wall & Jenkins 2003). Systems with more than three variables require higher order formulations. For a system of $N$ variables, the $(N - 2)$th-order partial correlation coefficient $r_{ij|1...N\setminus[ij]}$ of variables $x_i$ and $x_j$ can be written as

$$r_{ij|1...N\setminus[ij]} = \frac{-C_{i,j}}{\sqrt{C_{i,i}C_{j,j}}},$$

where $C_{i,j} = (-1)^{i+j}M_{i,j}$ (Kendall & Stuart 1977). $M_{i,j}$ is a reduced determinant of the correlation matrix $R$, where $R_{ij} = \rho_{ij}$, and $\rho_{ij}$ is the two-variable correlation coefficient of $x_i$ and $x_j$. The determinant $M_{i,j}$ can be interpreted as the total correlation among the variables of the system in the absence of $i$ and $j$. It is calculated from $R$ with the $i$th row and $j$th column eliminated (Kendall & Stuart 1977).

Given a partial correlation coefficient from Equation (2), we would like to know its significance. This can be evaluated from

$$\sigma_{ij|1...N\setminus[ij]} = \frac{1 - r_{ij|1...N\setminus[ij]}}{\sqrt{m - N}},$$

where $r_{ij|1...N\setminus[ij]}$ is the partial correlation coefficient given by Equation (2), $N$ is the number of variables in the system, and $m$ is the number of objects in the sample. The statistical significance of $r_{ij|1...N\setminus[ij]}$ is determined from the Student’s $t$-distribution with dispersion $\sigma_{ij|1...N\setminus[ij]}$ (Wall & Jenkins 2003).

Partial correlation analyses can take both parametric and non-parametric forms. These are analogous to the more commonly applied two-variable correlation analyses. Equation (2) can be applied to any of the correlation coefficients in common use. However, Equation (3) is defined for the parametric Pearson’s correlation coefficient, so it is appropriate only for that estimator or the closely related, non-parametric Spearman coefficient. We want a non-parametric approach, so we rely on Spearman correlation coefficients in our analysis.

4. COMPLETENESS CORRECTIONS

We wish to examine the distributions of stellar masses and SFRs described in Section 2.2 to probe the impact of the cluster environment on galaxy growth. However, to do this we must first correct for selection effects. The spectroscopic selection function that defines our sample is unknown, because many of the sources that contribute to the redshifts in the literature do not define their target selection functions or rates of success. Furthermore, the MIR observations do not uniformly cover the cluster fields. Therefore, we empirically determine both our spectroscopic and MIR selection functions to correct for these effects.

4.1. Spectroscopic Completeness

We examine only spectroscopically confirmed cluster members. Many of the redshifts we use come from Martini et al. (2007) which we supplemented with redshifts from other sources in the literature. This results in a complex selection function that is poorly known a priori. However, this completeness function is required to correct the properties of observed cluster galaxies to the intrinsic distribution for all cluster members. We take an empirical approach to determine spectroscopic completeness and correct the measured cluster members to the total cluster galaxy population.

For each cluster, we bin galaxies identified in the photometric source catalog by $V - R$ color, $R$-band magnitude, and $R/R_{200}$. We find significant variations in the fraction of galaxies with spectra ($f_{\text{spec}}$) as a function of $R/R_{200}$ and $m_R$, but the variation with color is at most minor. A partial correlation analysis of $f_{\text{spec}}$ as a function of color, magnitude, and position shows no significant partial correlation with $V - R$ at 95% confidence in any cluster, while $f_{\text{spec}}$ correlates with both $m_R$ and $R/R_{200}$ at >99.9% confidence. We therefore collapse the measurement along the color axis and determine the fraction of galaxies with spectroscopy as a function of $R$-band magnitude and position only. This results in better measurements due to the larger number of galaxies per bin.

The $f_{\text{spec}}$ measured above is one way to express the spectroscopic completeness of galaxies in a given magnitude–radius
have too few confirmed members to make a meaningful measurement. If a function of radius for the six clusters in our main sample. Two clusters in NCl values except for C, which is not a good tracer of spectroscopic completeness, bin. However, what we really want is an expression for the spectroscopic completeness, Cspec, of cluster members,

\[ C_{\text{spec}}(x) = \frac{N_{\text{Cl,spec}}(x)}{N_{\text{tot}}(x)} \]

where \( x \) is the position of a given bin in magnitude–radius space, \( N_{\text{Cl,spec}} \) is the number of galaxies with spectra that are cluster members, \( N_{\text{Cl}} \) is the number of true cluster members, \( N_{\text{spec}} \) is the number of galaxies with spectra in the cluster field, and \( N_{\text{tot}} \) is the number of galaxies in the input catalog. All of these quantities except \( N_{\text{Cl}} \) can be measured directly from the input catalogs. We would need to infer \( N_{\text{Cl}} \) using some additional piece of information, so we prefer to rely on \( f_{\text{spec}} \) rather than \( C_{\text{spec}} \) if possible.

If the redshifts reported in the literature were not pre-selected for cluster membership or if the redshift failure rate was high, \( f_{\text{spec}}(x) \) would be a good proxy for \( C_{\text{spec}}(x) \), and the approach in Equation (4) would be unnecessary. That would imply that the product of the last two terms in Equation (5) would be approximately 1. If this were the case, the fraction of galaxies with spectra that are cluster members (\( f_{\text{mem}} = N_{\text{Cl,spec}}/N_{\text{spec}} \)) should drop with \( R/R_{200} \) as the fraction of field galaxies increases. Figure 1 shows that \( f_{\text{mem}} \) does not always trace the decline in the density of cluster galaxies. In fact, \( f_{\text{mem}} \) is approximately constant in all six clusters. This implies that \( f_{\text{spec}} \) is not a good tracer of \( C_{\text{spec}} \), and the more sophisticated approach of Equation (4) is required.

Before we can employ Equation (4), we need to know the number of cluster galaxies in each bin. To do this, we estimate the number of field galaxies in the bin with the \( R \)-band magnitude–number density relation reported by Kümml & Wagner (2001). We subtract the field galaxies from the total number of galaxies in the bin to estimate the number of cluster galaxies.

This approach introduces two types of uncertainty. The first is simple Poisson counting uncertainty due to the small number of field galaxies, typically a few to 10, in each bin. The second is cosmic variance. Ellis (1987) reports a \( B \)-band magnitude–number density relation that includes measurements from a number of other authors. The different surveys use fields of different sizes, so the scatter of their results about the best-fit relation provides a measure of the cosmic variance, which contributes of order 10% uncertainty on the number of field galaxies in a typical bin. The number of field galaxies in a given bin depends on magnitude, but it generally ranges from 1 to 10 galaxies. At faint magnitudes, the number of field galaxies is generally comparable to the number of cluster galaxies, and Poisson fluctuations in the number of field galaxies dominate the uncertainties in the completeness measurements. The spectroscopic completeness measurements and associated uncertainties for each cluster are summarized in Table 1.

Figure 2 shows the spectroscopic completeness (\( C_{\text{spec}} \)) for six of the eight galaxy clusters in our sample. The remaining two clusters (A644 and A2163) have too few confirmed members to make a reliable measurement. The dashed, vertical lines on the right column of Figure 2 indicate the observed magnitude that corresponds to \( M_R = -20 \) for the average \( K \)-correction in each cluster. The follow-up spectroscopy of X-ray sources conducted by Martini et al. (2006) is only complete to this point.
luminosity limit. The majority of redshifts for cluster members in our sample came from spectroscopy conducted by Martini et al. (2007). They took spectra in multiple plates in each cluster field, so spectral collisions between cluster members do not substantially affect completeness, even near the cluster center. Clearly, completeness becomes quite poor for $M_B > -20$ in all clusters, so we restrict our sample to galaxies with $M_B < -20$.

We also examined completeness as a function of luminosity and stellar mass instead of apparent magnitude ($m_R$). However, these quantities have higher uncertainties than observed magnitudes, especially for galaxies without spectroscopic redshifts to fix their distances. Therefore, we measure completeness as a function of observed $R$-band magnitude and $R/R_{200}$.

### 4.2. Mid-infrared Completeness

The depth of the MIR images varies as a function of position across the clusters. This is a result of the Spitzer mosaicking schemes, which were chosen to provide good coverage of the known X-ray point sources in the cluster. These mosaic schemes lead to variations in the number of overlapping images, and therefore to variations in sensitivity, across the cluster fields.

In addition to these sensitivity variations, the Spitzer footprint features some non-overlapping coverage by the different IRAC bands. This results from the IRAC mapping strategy, which simultaneously images two adjacent fields in different bands. The pointings chosen by the observer then determine the degree of overlap between the IRAC channels. For a galaxy to enter the final sample, it must include detections in at least five bands to ensure that the fit results for that galaxy are well constrained.

This means that a faint galaxy in a region of a cluster with overlapping 3.6 μm and 4.5 μm images, for example, might be more likely to appear in the final sample than an identical galaxy in a part of the cluster with only 4.5 μm coverage. However, this requirement only eliminates one galaxy with a detection at either 8 μm or 24 μm.

To construct ensemble statistics for whole clusters, we require sensitivity corrections that account for variable depth across the cluster fields and for the different footprints in the Spitzer bands, as shown in Figure 3. We again take an empirical approach to completeness correction. We measure the MIR flux uncertainties at the locations of all confirmed cluster members from the Spitzer uncertainty mosaics. At each position, we combine the two Assef et al. (2010) star-forming templates with arbitrary flux normalizations 1000 times to produce galaxies with $10^{-2} < \text{SFR}/(1 \text{ M}_\odot \text{ yr}^{-1}) < 10^2$. From these artificial galaxy SEDs, we construct model fluxes and determine whether the galaxy represented by each SED would have been detected at 3σ based on the flux uncertainty at each position. We bin the results by flux and by $R/R_{200}$ to estimate completeness separately at 8 μm and 24 μm. Figure 4 shows the results of this measurement for the six clusters in Figure 2. IRAC and MIPS completenesses clearly depend on both flux and $R/R_{200}$.

The uncertainties in MIR completeness result from the incomplete spectroscopic sampling of the galaxies in a given bin. We implicitly assume that the identified cluster members in each bin are representative of the behavior of the unidentified members. This assumption means that the precision of the completeness correction in a given bin is fixed by the number of identified galaxies observed in that bin.
Figure 3. IRAC (blue) and MIPS (red) footprints overlaid on the R-band images for each cluster shown in Figure 2. The Spitzer observations are clearly not azimuthally symmetric. The projected $R_{200}$ for each cluster is shown for reference (green).

(A color version of this figure is available in the online journal.)

Figure 4. MIR completeness as a function of flux for the $8 \mu m$ (left) and the $24 \mu m$ (right) Spitzer bands. In each column, the sample has been separated into four radial bins. Fluxes have not been color corrected and are given in the observer frame. Uncertainties are shown for a single radial bin to indicate typical values. MS 1008.1-1224 was not observed with MIPS. Completeness measurements are derived as described in Section 4.2.

(A color version of this figure is available in the online journal.)
Table 2  
MIR Completeness

|     | $R/R_{200}$ | $f_{\nu}(8 \mu m)(Jy)$ | $C_{8,\mu m}$ | $f_{\nu}(24 \mu m)(Jy)$ | $C_{24,\mu m}$ |
|-----|-------------|------------------------|--------------|------------------------|--------------|
| A3128 | 0.06        | $2.65 \times 10^{-4}$  | 0.00$^{+0.15}_{-0.00}$ | 1.70 $\times 10^{-4}$  | 0.00$^{+0.15}_{-0.00}$ |
|      | 0.06        | $8.44 \times 10^{-4}$  | 0.51$^{+0.14}_{-0.17}$ | 5.41 $\times 10^{-4}$  | 0.00$^{+0.15}_{-0.00}$ |
|      | 0.06        | $2.69 \times 10^{-3}$  | 0.55$^{+0.14}_{-0.20}$ | 1.64 $\times 10^{-3}$  | 0.31$^{+0.16}_{-0.17}$ |
|      | 0.06        | $8.57 \times 10^{-3}$  | 0.55$^{+0.14}_{-0.20}$ | 5.44 $\times 10^{-3}$  | 1.00$^{+0.00}_{-0.00}$ |
|      | 0.06        | $2.66 \times 10^{-2}$  | 0.54$^{+0.14}_{-0.20}$ | 1.74 $\times 10^{-2}$  | 1.00$^{+0.00}_{-0.00}$ |
|      | 0.06        | $8.48 \times 10^{-2}$  | 0.54$^{+0.14}_{-0.20}$ | 5.51 $\times 10^{-2}$  | 1.00$^{+0.00}_{-0.00}$ |
|      | 0.06        | $2.73 \times 10^{-1}$  | 0.54$^{+0.14}_{-0.20}$ | 1.64 $\times 10^{-1}$  | 1.00$^{+0.00}_{-0.00}$ |
| A3125 | 0.05        | $2.53 \times 10^{-4}$  | 0.00$^{+0.15}_{-0.00}$ | 1.58 $\times 10^{-4}$  | 0.00$^{+0.15}_{-0.00}$ |
|      | 0.05        | $7.95 \times 10^{-4}$  | 1.00$^{+0.00}_{-0.50}$ | 5.09 $\times 10^{-4}$  | 1.00$^{+0.00}_{-0.50}$ |
|      | 0.05        | $2.40 \times 10^{-3}$  | 1.00$^{+0.00}_{-0.50}$ | 1.57 $\times 10^{-3}$  | 1.00$^{+0.00}_{-0.50}$ |
|      | 0.05        | $7.89 \times 10^{-3}$  | 1.00$^{+0.00}_{-0.50}$ | 5.03 $\times 10^{-3}$  | 0.58$^{+0.08}_{-0.08}$ |
|      | 0.05        | $2.50 \times 10^{-2}$  | 1.00$^{+0.00}_{-0.50}$ | 1.60 $\times 10^{-2}$  | 1.00$^{+0.00}_{-0.50}$ |
|      | 0.05        | $7.84 \times 10^{-2}$  | 1.00$^{+0.00}_{-0.50}$ | 4.93 $\times 10^{-2}$  | 1.00$^{+0.00}_{-0.50}$ |
|      | 0.05        | $2.56 \times 10^{-1}$  | 1.00$^{+0.00}_{-0.50}$ | 1.57 $\times 10^{-1}$  | 1.00$^{+0.00}_{-0.50}$ |

Notes. Column (1) gives the cluster name. Column (2) gives the median radius, scaled to the virial radius of the cluster, of galaxies that go into the bin. Columns (3) and (5) give the median observed frame fluxes in the 8 μm and 24 μm channels, respectively, of the model SEDs that make up each bin. Fluxes are calculated integrating model SEDs with random combinations of the Assef (3) star-forming templates across the published instrument response functions. If the SFRs inferred from the rest-frame luminosities in the model SEDs are outside the range 10$^{-2}$ < SFR/(1 M$_{\odot}$ yr$^{-1}$) < 10$^{2}$, the associated fluxes are not included in the sample. Because the Assef (3) templates are not constructed to have identical SFRs in the 8 μm and 24 μm channels, this sometimes means that an SED with a valid SFR in one channel will not appear in another. When a flux bin is occupied in one channel and not in another, the empty channel has $f_{\nu} = 0$ and C$_{\nu} = -1$. This is the case for the first flux bin in AC114. Columns (4) and (6) give the MIR completeness (C$_{\nu}$) as defined in Section 4.2. (This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

4.3. Merged Cluster Sample

We have defined the MIR completeness measurements in Figure 4 so they apply only to galaxies with spectroscopic redshifts. The spectroscopic and MIR completeness corrections, applied serially, yield total completeness corrections. The total correction $X_{G}$ for a galaxy G is

$$X_{G} = \frac{1}{C_{spec}(R_{G}/R_{200}, m_{R,G})} \times \frac{1}{C_{MIR}(R_{G}/R_{200}, f_{\nu,G})},$$

where $C_{spec}$ is the spectroscopic completeness (Figure 2) and $C_{MIR}$ is the MIR completeness (Figure 4). Applied to individual cluster members, the completeness corrections described by Equation (6) allow us to extrapolate from the measured galaxy samples to the full cluster population. In cases where multiple corrections can be derived for a single object, we combine these corrections in the same way the data are combined. For example, the completeness correction for a galaxy with SFR measurements from both 8 μm and 24 μm fluxes is given by $X = [X_{8,\mu m}X_{24,\mu m}]^{1/2}$ because SFR = $[SFR_{8,\mu m}SFR_{24,\mu m}]^{1/2}$. (See Section 2.2.)

To examine the dependence of star formation and black hole growth on environment, we need to construct a merged cluster galaxy sample. We identify five clusters (A3128, A2104, A1689, MS1008, and AC114) with the best completeness measurements and combine their members. The relatively small number of galaxies in A3125 results in highly irregular behavior of the completeness functions. As a result, any corrections we applied would depend critically on the binning scheme. We therefore exclude it from the main cluster sample.

The clusters in the main sample can be combined to yield better statistics. To construct the combined cluster, we weight individual galaxies by their completeness corrections ($X_{G}$). The correction is a combination of the spectroscopic and photometric completeness corrections from Sections 4.1 and 4.2, as given by Equations (4)–(6).

5. LUMINOSITY FUNCTIONS

LFs provide an important diagnostic for the difference between cluster galaxies and field populations, because LFs are sensitive to the entire cluster population rather than only the average. For example, Bai et al. (2009) employed the TIR LF to infer that RPS controls the evolution of SFRs in cluster galaxies. In this section, we discuss the derivation of TIR luminosities and our method to construct LFs. We discuss the results in Section 6.4.

5.1. Total Infrared Luminosity

Our MIR observations cover a relatively narrow wavelength range from 3.6 μm to 24 μm. To compare our results with previous studies, we need to infer $L_{TIR}$ from the observed MIR luminosities, so we must apply bolometric corrections (BCs). To estimate $L_{TIR}$ from the Spitzer observations, we employ the Dale & Helou (2002) SED template library, which includes a wide variety of SEDs. These SEDs differ from one another in the intensity of the radiation field on a typical dust grain, which Dale & Helou (2002) parameterize as $\alpha$.

Before we calculate BCs for IR AGNs, we first subtract the AGN contribution (Paper I). We then fit each Dale & Helou (2002) template to the rest-frame 5.8, 8.0, and 24 μm fluxes and use the template that best fits the data to measure our fiducial BCs. In the frequent cases where luminosities in one or more of these bands are unavailable, we estimate the missing luminosities from model SEDs (Assef et al. 2010). When this is necessary, we use the uncertainties on the model SED to assign uncertainties to the model fluxes. We only calculate $L_{TIR}$ for galaxies with detections in at least one of the 8 μm and 24 μm bands.

In galaxies that have measurements of both $L_{8,\mu m}$ and $L_{24,\mu m}$, we calculate $L_{TIR}$ separately for each band and take the geometric mean of the results. This follows our treatment of SFRs in Paper I. In other cases, we simply use the BC appropriate...
for the band where we have a detection. We also construct 68% confidence intervals for each BC based on the $\Delta \chi^2 = 1$ interval for each galaxy. These uncertainties are asymmetric, and they add in quadrature to the uncertainties on $L_{8\mu m}^{\text{TIR}}$ and $L_{24\mu m}^{\text{TIR}}$ to give the total uncertainty on $L_{\text{TIR}}^{\text{w}}$. Typical BCs are $\sim 6$ for $L_{8\mu m}^{\text{TIR}}$ and $\sim 8$ for $L_{24\mu m}^{\text{TIR}}$.

5.2. Luminosity Function Construction

We construct LFs from galaxies in the main cluster sample whose luminosities ($L$) we describe as having asymmetric upper ($\sigma_u$) and lower ($\sigma_l$) uncertainties. We calculate the TIR luminosities ($L_{\text{TIR}} = L_{\text{TIR}}^{\text{w}}$) needed to construct LFs as described in Section 5.1. If we account for the uncertainties on $L_{\text{TIR}}$, we can reduce our sensitivity to Poisson fluctuations in the number of luminous galaxies. We distribute the galaxy weights described in Section 4 over luminosity bins according to the probability that the true luminosity of a galaxy with best estimate $L = L_{\text{TIR}}^{\text{w}}$ lies in a given bin. Due to the uncertainty on the LF prior, this technique increases the statistical uncertainty on the total weight in each bin by $\sim 10\%$. In exchange, we reduce the much larger uncertainty introduced by stochasticity in the number of luminous galaxies.

To distribute galaxy weights over luminosity bins, we employ an asymmetric probability density function (PDF) that considers $\sigma_l$ and $\sigma_u$ separately. We integrate the PDF across each luminosity bin to determine the weight in each bin, which we add to construct the total LF. The PDF we employ is piecewise smooth, and it approaches the normal distribution when $\sigma_u \approx \sigma_l$. It is described in more detail in the Appendix.

In addition to the PDF, we require a prior on the shape of the LF to correct for Eddington-like bias due to the steepness of the LF above $L^\ast$. We adopt a Schechter function fit to the Coma Cluster LF from Bai et al. (2006) as the baseline prior. We then correct the Coma LF to the redshift of each individual cluster according to the evolution of the field galaxy LF (Le Floc’h et al. 2005). We add the uncertainty on the prior to the statistical uncertainty on the LF in each luminosity bin. The prior has a strong impact on the bright-end shape of the LF because there are few cluster galaxies to constrain the LF in this regime. The results are discussed in Section 6.4.

6. RESULTS

We apply the weights derived from the completeness corrections described in Section 4 to the main cluster sample, which is a subset of the cluster galaxies in Table 3 taken from the five best clusters. These completeness corrections allow us to examine the average environmental dependence of $M_*$ (Section 6.2) and SFR (Sections 6.3–6.5), and the redshift dependence of star formation (Section 6.6). Before conducting these analyses, we perform a partial correlation analysis to determine which observed properties of galaxies in clusters most strongly correlate with star formation (Section 6.1). The results inform the rest of our work.

6.1. Partial Correlation Analysis

The cluster environment can significantly alter the evolution of cluster member galaxies, as described in Section 1. However, when we attempt to distinguish between the physical properties that might cause these effects, we confront a system of mutually correlated observables. For example, SFR depends on both projected local galaxy density to the 10th nearest neighbor ($\Sigma_{10}$; Osterbrock 1960; Oemler 1974; Dressler 1980; Kauffmann et al. 2004) and position within the cluster ($R/R_{200}$; Kodama & Bower 2001; Balogh et al. 2004; Christlein & Zabludoff 2005; Blanton & Berlind 2007; Hansen et al. 2009; von der Linden et al. 2010). Figure 5 demonstrates the correlations between SFR, position, projected galaxy density, and $M_*$ among SFGs. It is not immediately clear which of these is the most fundamental.

While the causal connection between morphology and the local density of galaxies is well established (e.g., Dressler 1980; Dressler et al. 1999; Postman et al. 2005), Moran et al. (2007) find strong evidence that the morphologies and SFRs of massive spiral galaxies in clusters evolve separately. This implies that a
factor other than local density may control star formation in cluster galaxies. Because $M_\ast$, $R/R_{200}$ and projected local density ($\Sigma_{10}$) are all mutually correlated, it is not easy to determine which variable(s) drive the environmental dependence of star formation. Therefore, we use a partial correlation analysis to disentangle these dependencies. The mathematical formalism for partial correlation analysis is described in Section 3. We do not consider completeness corrections for this analysis, so we include galaxies from all eight clusters.

We consider only objects with measurements of all parameters under consideration and ignore galaxies with upper limits. This differs from the similar analysis conducted by Christlein & Zabludoff (2005), who also considered upper limits. As a result, our results are more sensitive than those of Christlein & Zabludoff (2005) to systematic effects like variations in sensitivity within or between clusters. Because of this, we do not rely directly on the strength of any partial correlations, but only on the presence or absence of such correlations. We also combine galaxies from all five clusters in the main sample, which allows us to account for incompleteness statistically. (See Sections 6.2–6.6.)

We perform a partial correlation study on a system of four variables: SFR, $M_\ast$, $R/R_{200}$, and projected local density of cluster members ($\Sigma_{10}$). We exclude galaxies with $R > 0.4 R_{200}$ from this analysis to avoid potential biases due to higher SFRs and smaller angular sizes among high-$z$ clusters. The partial correlation coefficients returned by the analysis are listed in Table 4.

Table 4 shows that the SFRs of SFGs increase significantly with $M_\ast$ ($r_{S,\text{partial}} = +0.253$), but it shows no residual dependence of SFR on $R/R_{200}$ once the influence of $M_\ast$ has been factored out ($r_{S,\text{partial}} = +0.04$). The dependence of SFR on mass but not $R/R_{200}$ agrees with earlier results, which generally find either that SFR depends only on $M_\ast$ (Grützbauch et al. 2011; Rettura et al. 2011) or that SFR depends on both $M_\ast$ and environment (Christlein & Zabludoff 2005). However, the results in Table 4 include only SFGs. As a result, we find a positive correlation of SFR with $M_\ast$, which is similar to the results of

![Figure 5](image_url)

Figure 5. Correlations of star formation with position in the cluster (top row), projected local density (middle row), and stellar mass (bottom row). Galaxies with no measurable star formation are neglected. Colors denote the different clusters in the sample: A3128 (black), A3125 (red), A644 (blue), A2104 (green), A1689 (cyan), A2163 (magenta), MS1008 (orange), and AC114 (violet). Large black points show the median values of the galaxy sample after it has been binned by SFR. SFR among SFGs shows a significant correlation only with $M_\ast$ ($r_S = +0.24, P = 0.02$). The dashed line in the bottom panel separates galaxies whose dust luminosities (and inferred SFRs) are consistent with AGB dust in passive galaxies (Haines et al. 2011). These galaxies have been excluded from our analysis. Partial correlation coefficients derived from these data are listed in Table 4.

(A color version of this figure is available in the online journal.)

| Table 4 Partial Correlation Results |
|------------------------------------|
| (1) | (2) | Partial $r_S$ | Prob. |
|-----|-----|---------------|-------|
| SFR | $M_\ast$ | +0.253 | 9.54 $\times 10^{-3}$ |
| SFR | $R/R_{200}$ | +0.041 | 7.02 $\times 10^{-1}$ |
| SFR | $\Sigma$ | -0.132 | 5.53 $\times 10^{-1}$ |
| $M_\ast$ | $R/R_{200}$ | +0.092 | 5.18 $\times 10^{-1}$ |
| $M_\ast$ | $\Sigma$ | +0.164 | 6.52 $\times 10^{-1}$ |
| $R/R_{200}$ | $\Sigma$ | -0.568 | 8.39 $\times 10^{-13}$ |

Notes. Partial correlation results for star-forming galaxies derived from the Spearman correlation coefficients for the variables listed in Columns (1) and (2). Column (3) gives the strength of the correlation between the two variables with the other parameters held fixed. Column (4) gives the probability that a correlation at least as strong as that observed might occur by chance among intrinsically uncorrelated data.
Grützbauch et al. (2011) in 1.5 < z < 3 clusters. This stands in contrast to Christlein & Zabludoff (2005), who included both SFGs and passive galaxies to find an anti-correlation of SFR with $M_\star$. Such a positive correlation of SFR with $M_\star$ is consistent with the RPS scenario, in which massive galaxies retain a larger fraction of their cold gas than their less massive counterparts. We note, however, that SFGs in the field also exhibit a correlation of SFR with $M_\star$. This is known as the “main sequence” of SFGs (Elbaz et al. 2007), and we cannot distinguish these explanations without additional modeling.

We also performed a two-variable correlation test to determine whether local substructure, as measured by the Dressler & Shectman (1988) substructure parameter ($\delta$), significantly impacts SFRs among SFGs in clusters. We found no correlation between $\delta$ and SFR ($r_S = -0.03$). This conflicts with Christlein & Zabludoff (2005), who reported a strong correlation of SFR with local substructure. However, $\delta$ requires a robust spectroscopic sample from which to measure local velocity dispersions. As a result, the substructure measurements for some of our clusters with less complete spectroscopy are probably unreliable.

We repeat the test with A3128 and A3125, which have the most complete spectroscopy and are the only two clusters with significant substructure. The results are indistinguishable from the full cluster sample.

### 6.2. Mass–Radius Relation

In Section 6.1, we reported a strong correlation of SFR with $M_\star$ but no residual dependence of $M_\star$ on radius. This might indicate that $M_\star$ is independent of environment, as von der Linden et al. (2010) found. However, it might also mean that the SFR–$M_\star$ correlation is strong enough to eclipse any more subtle correlations that might appear among a sample composed entirely of SFGs. The galaxy sample examined in Section 6.1 includes only a few hundred galaxies, and the sample preferentially excludes the most massive galaxies, which tend not to show active star formation. As a result, Section 6.1 might show no correlation between $M_\star$ and $R/R_{200}$, even if the full cluster galaxy sample includes one. Christlein & Zabludoff (2005) found a strong partial correlation of mass with $R/R_{200}$. This correlation would be difficult to produce if brightest cluster galaxies (BCGs) alone produce a false correlation of $M_\star$ with $R/R_{200}$, as von der Linden et al. (2010) claim, because normal cluster galaxies are much more numerous than BCGs.

To test whether our data support the presence of a radial trend in $M_\star$, we look for radial variations in the populations of low- and high-mass galaxies. We first divide the galaxy sample into two samples with equal numbers of galaxies, and we apply a K-S test to check for a difference between their radial distributions. For this analysis, we include members of all eight clusters, and we exclude BCGs as defined by von der Linden et al. (2007) from the sample. The results are shown in Figure 6(a). The K-S test returns a probability $<0.1\%$ that the high- and low-mass samples have the same radial distributions, so massive galaxies in our sample are preferentially found closer to the centers of their parent clusters, even in the absence of BCGs. We weight members of the main cluster sample by their completeness to determine the average mass as a function of radius. The average mass in a given bin is

$$
\langle M_\star \rangle = \frac{\sum_{i=0}^N [w_i M_{\star,i}]}{\sum_{i=0}^N [w_i]},
$$

where $N$ is the number of galaxies in the bin with $M_R < -20$. The $w_i$ are the weights derived from Equation (4).

![Figure 6](https://example.com/figure6.png)

**Figure 6.** Radial distributions of all cluster members scaled to $R_{200}$. Panel (a) compares the radial distributions of low-mass (blue dashed) and high-mass (red solid) galaxies, divided into two equally sized subsamples at $M_{\text{int}} = 3.9 \times 10^{10} M_\odot$. The two distributions differ at 99.9% confidence after we exclude BCGs as defined by von der Linden et al. (2007). Panel (b) compares the radial distributions of galaxies with (blue dotted) and without (red dashed) an 8 $\mu$m flux excess to the distribution of all galaxies with $8 \mu$m detections (heavy black). The distribution of galaxies with no measurable excess shows a marginal difference compared to the distribution of all cluster members (95% confidence).

(A color version of this figure is available in the online journal.)

Figure 7 shows the resulting average masses as a function of radius.

Processes like tidal stripping and dynamical friction, which can both introduce radial trends in $M_\star$, scale with density. As a result, we might expect that the combined effects of these processes might introduce a power-law dependence of mass on $R/R_{200}$. Figure 7 clearly demonstrates that no single power law can fit the observed masses over the entire range considered. Instead, the innermost radial bin in Figure 7 shows a strong excess compared to the other bins, and the second bin hints at an excess. To determine the strength of the excess in the inner bins, we will assume that the six outer bins in Figure 7 can be adequately fitted by a single power law (solid line). We use this fit to measure the strength of the mass excess in the inner two bins and to determine why our results differ from those of von der Linden et al. (2010).

Figure 7 shows that the average masses of galaxies near the cluster center show an excess compared to their counterparts further out in the cluster. The innermost radial bin in Figure 7 differs from the best-fit model by 2.8$\sigma$, and the mass excess in the second radial bin is significant at 1.8$\sigma$. The semi-analytic models of Book & Benson (2010) show increases in $\langle M_\star \rangle$ for radii $R/R_{\text{virial}} \lesssim 0.05$, which is consistent with our results in Figure 7. The observed increase indicates that the cluster core $R \lesssim 0.05 R_{200}$ tends to host more massive galaxies than the outer regions, even if we neglect BCGs. Mass segregation among cluster galaxies can be introduced as the cluster relaxes to virial equilibrium. Under the simple approximations that
galaxies follow an $R^{-2}$ radial distribution and that the number of galaxies grows linearly with cluster mass, we can apply the Chandrasekhar dynamical friction formula to infer relaxation times. For a “typical” cluster with $\sigma = 1200 \text{ km s}^{-1}$ at $z = 0.15$, we infer a relaxation time of approximately 300 Myr in the inner radial bin ($R/R_{200} < 0.05$). The core of a typical cluster in our sample should therefore be dynamically relaxed; however, for the same cluster, the crossing time for the sphere defined by $R \lesssim 0.4 R_{200}$ is approximately 900 Myr. This crossing time implies a dynamical relaxation time of 7 Gyr (Binney & Tremaine 2008, Section 8.1), which is longer than the age of a cluster at $z = 0.15$ that “assembled” at $z = 1$ (5.8 Gyr), so we expect that the sphere with $R \lesssim 0.4 R_{200}$ would not have had time to relax at the average redshift for clusters in our sample.

Figure 7 suggests a reason for our disagreement with von der Linden et al. (2010). The signal comes primarily inside galaxies follow an $R^{-2}$ radial distribution. Brightest cluster galaxies, as defined by von der Linden et al. (2010), are excluded from the average because of their unusually large stellar masses and SFRs compared to other galaxies near the centers of clusters (von der Linden et al. 2007). The heavy line indicates the best-fit power law to the six outer bins. The two innermost radial bins were excluded from the fit based on their apparent excesses. Their exclusion results in a reduction in total $\chi^2$ from 9.1 to 1.0. The best fit yields $M_* \propto \left[R/R_{200}\right]^{0.10 \pm 0.02}$, and the shaded region indicates the 68% confidence interval to the fit. The residuals are shown in the lower panel.

6.3. Environmental Dependence of SFR

In Paper I, we examined the $R/R_{200}$ distributions of AGNs and found no significant difference between the positions of AGNs and normal cluster members. The lack of measurable radial dependence among AGNs could be due to the small sample size; it could also indicate a weak dependence of the amount of cold gas on $R/R_{200}$, or it might mean that AGN fueling is poorly correlated with the total cold gas reservoir of its host galaxy. To test these hypotheses, we define a sample of galaxies with 8 $\mu$m flux excesses as those galaxies whose measured 8 $\mu$m flux exceeds the flux expected from a passively evolving galaxy matched in $M_K$ at more than 2$\sigma$. Figure 6(b) compares the radial distributions of galaxies with and without an 8 $\mu$m excess. These objects include both SFGs and AGNs. We again excluded BCGs from these samples. The radial distribution of galaxies with 8 $\mu$m excesses is indistinguishable from the merged sample, but galaxies without an excess are located closer to the centers of their host clusters than the average cluster galaxy at 95% confidence.

The tendency of galaxies with minimal dust emission to have low $R/R_{200}$, as shown in Figure 6(b), is consistent with the established dependence of SFR on position within galaxy clusters (Kodama & Bower 2001; Balogh et al. 2004; Christlein & Zabludoff 2005; Hansen et al. 2009; von der Linden et al. 2010). One way to test the origin of this effect, and by extension the SFR–density and SFR–radius relations, is to measure the average SFR as a function of radius. We weight individual SFGs by their total completeness (Equation (6)) and bin them in radius to determine <SFR>:

$$<\text{SFR}> = \frac{\sum_{i=0}^{N_{\text{SF}}} [w_j SFR_i]}{\sum_{i=0}^{N_{\text{SF}}} [w_j]}$$  (8)

where $w_{i,j}$ are the weights for SFGs and all galaxies, respectively. For this calculation, we define SFGs as all galaxies with SFR $\geq 3 M_\odot \text{ yr}^{-1}$. This guarantees that we are not subject to biases due to variable sensitivities across the cluster fields. We also exclude galaxies whose dust luminosities are consistent with dust heated by asymptotic giant branch (AGB) stars in old stellar populations (Figure 5). We fit a power law to <SFR> as a function of $R/R_{200}$ and find

$$\log_{10}[\text{SFR}] = (1.1 \pm 0.3) \log_{10}[R/R_{200}] + (1.0 \pm 0.2),$$  (9)

where SFR is the average in each radial bin. The fit yields $\chi^2_\nu = 1.2$ and is shown by the solid line on the upper panel with the 1$\sigma$ uncertainty given by the gray region.

The red line in Figure 8 shows the gradient predicted by the model of Book & Benson (2010), who applied RPS to the hot gas in cluster galaxies to model star formation in these galaxies, we have normalized the red line in Figure 8 to minimize the $\chi^2$ between the model and the observed SFRs, which may have been necessary because their model is appropriate for $z = 0$ clusters rather than the $z_{\text{median}} = 0.15$ appropriate for the combined galaxy sample in Figure 8. The figure demonstrates that the
Figure 8. Averaged star formation in the combined cluster sample as a function of position. Each panel shows two different binning schemes: fine (black squares) and coarse (orange triangles) for the same galaxy samples. The top panel shows average SFR among all galaxies. The solid line indicates the best-fit power law and coarse (orange triangles) for the same galaxy samples. The middle panel shows the averaged SFR at Rpassive evolution. However, a fit to the data (⟨SFR⟩ ∝ [R/R200]−1.0±0.3) and the red line shows the gas starvation model of Book & Benson (2010), normalized to match the observed SFRs. The shaded region indicates the 1σ confidence interval to the fit. The middle panel shows the fraction of SFGs (SFR > 3 M⊙ yr⁻¹) as a function of position, with the best fit (fSFR ∝ [R/R200]−2.3±0.16) shown by the line and the 1σ confidence interval shown by the shaded region. The bottom panel shows the averaged SFR among SFGs (⟨SFR⟩SFG) vs. R/R200. Galaxies with R/R200 ≤ 0.1 have lower ⟨SFR⟩SFG than galaxies outside 0.1 R200 at >99.9% confidence.

(A color version of this figure is available in the online journal.)

renormalized Book & Benson (2010) model provides a poor match to our data (χ² = 2.6), which may reflect the importance of physical effects not included in their model (e.g., ram pressure on cold gas).

Despite the significant uncertainty in the power-law fit to the SFR–radius relation, Figure 8 clearly demonstrates higher (SFR) toward the outer regions of the combined cluster sample. To interpret Equation (9) in detail, we need a model that better agrees with the observations than the Book & Benson (2010) model and that accounts for projection effects, the distribution of orbits followed by cluster members, and the effect of different environmental processes.

The RPS scenario makes at least one clear, qualitative prediction that we can use to evaluate its impact without a detailed model. Because RPS operates quickly compared to the cluster crossing time, the radial variation in (SFR) should be caused by variations in the fraction of SFGs (fSFR), and there should be little change in the SFRs of individual SFGs. The middle panel of Figure 8 shows that fSFR declines strongly near the cluster center, which is consistent with RPS. We also see lower (SFR) among SFGs with R ∼ 1 R200 compared to SFGs with R > 0.1 R200 (bottom panel). This difference is formally significant at >99.9% confidence, so SFGs with R ∼ 1 R200 experience a clear reduction in their SFRs as they transition to passive evolution. However, a fit to (SFR)SFG versus R/R200 shows a significant trend, which implies that the reduction in SFR at R ∼ 1 R200 is better described as a sharp transition rather than a gradual decline. The time to cross this region is approximately 100 Myr, which is consistent with the time required to strip gas from a typical spiral galaxy (Kapferer et al. 2009). The onset of this break, however, occurs much closer to the cluster center than the radius at which RPS is expected to become important (~0.5 R200; Treu et al. 2003).

6.4. TIR Luminosity Function

Another probe of the impact of environment on star formation is the TIR LF. The TIR LF is sensitive to the frequency of star formation in clusters and the rapidity with which it is quenched; this provides a strong empirical constraint on the types of processes that mediate the interaction between individual galaxies and the cluster environment. For example, Bai et al. (2009) find similar shapes (α and L∗) of the TIR LFs in the galaxy clusters that they measure compared to the field galaxy TIR LF. They argue that this similarity requires truncation of star formation on short timescales compared to the lifetime of star formation in individual galaxies. Such rapid transitions are inconsistent with slower processes like gas starvation and galaxy harassment.

To evaluate the conclusion that RPS dominates the evolution of star formation in galaxy cluster members, we will examine the TIR LFs of the clusters in our main cluster sample. We construct their LFs as described in Section 5.2, and the results appear in Figure 9. The main cluster sample contains only five clusters, which prevents construction of subsamples that have different cluster masses and similar redshifts. Therefore, we cannot reliably identify effects that depend primarily on cluster mass.

The dashed vertical line in Figure 9 marks the expected Lthresh of a galaxy with the Assef et al. (2010) spiral SED and M_R = −20. This marks the approximate TIR completeness limit imposed by the requirement that M_R ≤ −20. We call this limit Lthresh. This limit is representative only, and Figure 9 includes many cluster members that have M_R ≤ −20 and L_TIR < Lthresh. This is expected because cluster galaxies have lower ⟨sSFR⟩ than the field galaxies used to construct the Assef et al. (2010) templates. In fact, 65% of galaxies with M_R < −20 mag and measurable (>3σ) MIR emission are less luminous than Lthresh. This means that Lthresh is robust, and the true limit is lower than the nominal value established from the spiral galaxy template. To predict the true Lthresh, we would need a model for the truncation of star formation in clusters, which is exactly what we want to constrain. To be conservative, we restrict our fits to use only bins more luminous than Lthresh. Above this limit, we can be confident that the weights given by Equation (6) will correct to the full galaxy population.

Like Bai et al. (2009), we find that the individual clusters in Figure 9 have LFs that closely resemble the field galaxy LF at their respective redshifts. However, the individual cluster LFs include significant uncertainties due to their limited sample sizes and spectroscopic incompleteness. Systematic uncertainties in completeness corrections might be especially important. We can only apply completeness corrections in regions of the clusters where we have both spectra and MIR photometry, so azimuthal asymmetry in the cluster population would introduce significant bias.

To overcome some of these limitations, we have combined galaxies from the five clusters shown in Figure 9 and constructed their LF. The merged cluster sample averages over different selection functions, so it is less subject to systematic selection biases in individual clusters. Nevertheless, any hidden variables we do not account for in Section 4 would introduce residual
clusters reflects the small area subtended by the visible images of that cluster, which cannot be corrected by our completeness measurements. The other normalizations in Figure 10, along with the best-fit Schechter LF and the LF of the Coma Cluster (Bai et al. 2009). The Schechter function has the form

$$\Phi(L) = \frac{\Phi^*}{L^*} \left( \frac{L}{L^*} \right)^{\alpha} e^{-L/L^*},$$

(10)

where $\Phi(L)$ gives the projected surface density of sources at TIR luminosity $L$, $\alpha$ and $L^*$ are the usual Schechter function parameters. We fix $\alpha = -1.41$ in the fit to the cluster LF, which is the best-fit value for the Coma LF (Bai et al. 2006). Le Floc’h et al. (2005) suggest that the faint end of the LF cannot evolve much with redshift for $z \lesssim 1$, so the faint end of the LF in the Coma Cluster is likely to provide a good estimate of $\alpha$ in all galaxy clusters. The best fit to the combined main cluster sample has $L^* = (6.6 \pm 1.1) \times 10^{10} L_\odot$.

If clusters rapidly shut off star formation in galaxies that fall in from the field, as Bai et al. (2009) conclude, then only galaxies that have recently become cluster members will have measurable star formation, and the TIR LF of a cluster should have $L^*$ and $\alpha$ similar to the field galaxy LF at the same redshift. Therefore, we want to compare $L^*$ to the field galaxy LF at the median redshift of the combined galaxy sample, $z_{\text{med}} = 0.21$. Le Floc’h et al. (2005) found that the field galaxy LF evolves as $L^* \propto (1 + z)^{\eta}$, where $\eta = 3.2_{-0.6}^{+0.5}$. Pérez-González et al. (2005) studied the 12 $\mu$m LFs of field galaxies from $z = 0$ to $z = 3$ and found that the field galaxy LF at $z = 0.1$ has $L^*_{12\mu m} = 4.1 \pm 1.3 \times 10^9 L_\odot$ and $\alpha = 1.23 \pm 0.07$. We use the prescription of Takeuchi et al. (2005) to convert their $L^*$ to a TIR luminosity, which yields $L^*_{\text{TIR}} = 2.3 \times 10^{10} L_\odot$ at $z = 0.1$. We use the results of Pérez-González et al. (2005) and Le Floc’h et al. (2005) to construct the TIR LF for field galaxies at the median redshift of the combined cluster sample ($z_{\text{med}} = 0.211$), and we fit the normalization of the LF to the observed cluster galaxy LF. The result is shown as the blue, dashed line in Figure 10. The quality of the fit ($\chi^2 = 4.7$) is considerably poorer than the fit shown by the heavy, black line ($\chi^2 = 0.5$), which uses $\alpha$ from the Coma Cluster and fits for $L^*_{\text{TIR}}$ and $\phi^*$. While the absolute $\chi^2$ values cannot be used to evaluate the acceptability of the fits due to the presence of correlated errors in adjacent luminosity bins, the Coma-based LF improves the quality of the fit by $\Delta \chi^2 = 4.2$ compared to the field galaxy LF with only one additional free parameter.

Bai et al. (2009) found that the luminous ends of the TIR LFs of the Coma Cluster and A3266 have similar shapes and that the $L^*_{\text{TIR}}$ for these clusters are indistinguishable from the field galaxy LF. They argue that, because gas starvation operates slowly (Gyr timescales), the similar LF shapes in clusters and in the field imply the absence of a transition population and suggest that gas starvation is not a plausible mechanism to end
star formation among cluster member galaxies. The similarity between the combined cluster LF and the redshifted field galaxy LF for $L_{\text{TIR}} > 4 \times 10^{10} L_{\odot}$ is consistent with the conclusions of Bai et al. (2009). However, the combined cluster LF shown in Figure 10 displays a 4σ deficit of galaxies with moderate SFRs ($\text{SFR} \approx 5 M_{\odot} \text{yr}^{-1}$) compared to the expectation from the field LF.

The disagreement between the field and cluster galaxy LFs in Figure 10 could indicate the presence of a transition population. It is also possible that the discrepancy results instead from some selection effect not accounted for in our completeness estimates. The most obvious culprit for such an effect is some residual incompleteness in our sample.

To test for radial gradients in any potential population of SFGs in transition, we binned the galaxies in the main cluster sample into three radial bins with equal numbers of galaxy bins. The TIR LFs for the subsamples are shown in Figure 11. The $L_{\text{TIR}}$ increases slightly from the innermost to outermost radial bins, but this increase is not statistically significant. This marginal increase in $L_{\text{TIR}}$ in the innermost radial bin is qualitatively similar to the results of Bai et al. (2009), who also examined the radial dependence of the TIR LF with a very similar binning scheme. However, the fractional change in $L_{\text{TIR}}$ in the Coma Cluster is much larger than observed in Figure 11. The increase in $(\text{SFR})_{\text{SFG}}$ seen in Figure 8 in the same radial bins does not appear to affect $L_{\text{TIR}}$. This indicates that the change in $(\text{SFR})_{\text{SFG}}$ is driven by the frequency of galaxies with $\text{SFR} \approx 3 M_{\odot} \text{yr}^{-1}$, close to the completeness limit of our sample.

6.5. Substructure and Pre-processing

Von der Linden et al. (2010) found a trend toward increased (SFR) at larger $R/R_{200}$ than extended out to at least $2 R_{200}$. They concluded that pre-processing in groups contributes significantly to the SFR–density relation. Our observations do not extend past $R = 0.4 R_{200}$ so it is impossible to measure pre-processing directly. However, A3128 shows significant substructure, so we can compare it to the smooth clusters in the sample to probe how the presence of substructure affects SFRs in clusters. This allows us to indirectly test the impact of group-scale environments on SFGs, because coherent substructures in clusters should correspond to recently accreted groups.

Before we can compare the integrated SFRs in different clusters, we must first correct for the different numbers of galaxies in each cluster. The sSFR naturally accounts for this variation, and it is therefore a better quantity to compare between clusters. We employ a method analogous to Equation (8) to calculate the $(\text{sSFR})$ and compare A3128, which shows significant substructure, to the other clusters in the main sample. We find $(\text{sSFR}) = 6.3^{+0.5}_{-0.5} \times 10^{-12} \text{yr}^{-1}$ and $(\text{sSFR}) = 2.2^{+0.3}_{-0.3} \times 10^{-11} \text{yr}^{-1}$ in A3128 and in clusters without substructure, respectively. If we correct (sSFR) of A3128 to the mean redshift of the other clusters ($z = 0.241$), we find $(\text{sSFR}) = 1.1^{+0.3}_{-0.3} \times 10^{-11} \text{yr}^{-1}$. This is still lower than the average of the clusters without substructure at ~99.9% significance.

The difference between A3128 and the other clusters might be a result of the structure in A3128, or A3128 might simply...
have an unusually low (sSFR) for its redshift. In the latter case, the observed difference would be a result of cosmic variance. We compared A3128 with the four individual clusters without substructure, and we found that only MS1008 has a lower redshift-corrected (sSFR) than A3128. MS1008 is approximately 50% more massive than A3128, which might account for its low (sSFR). However, the typical dispersion in f_{\text{SF}} among nearby clusters with $\sigma \gtrsim 800$ km s$^{-1}$ is approximately 0.1 dex (Poggianti et al. 2006), so the observed deficit of (sSFR) in A3128 might result from a 3$\sigma$ excursion compared to a typical, coeval cluster. While this provides a marginally plausible explanation for the deficit of (sSFR) in A3128, the presence of substructure appears to be a more probable explanation. If the observed difference arose from groups that have recently fallen into the cluster, the excess sSFR in clusters without substructure would imply that the “average” group member is likely to have experienced pre-processing. Even if the substructure in A3128 can account for its unusually low (sSFR), this effect is unlikely to appear in our correlation analysis (Section 6.1) due to the lack of significant substructure in seven of the eight clusters we examine.

We also note that discussions that use integrated cluster star formation to infer the influence of the cluster environment can be affected by the methods used to identify and correct for AGNs. For example, we noted in Paper I that the IR and X-ray AGN selection techniques identify quite different samples. If we relied only on X-ray-based AGN selection, as some authors do, the MIR luminosity contributed by unidentified AGNs would lead to an overestimate in the integrated SFR of the cluster. For example, in A1689 we would overestimate the total SFR by 20%. Applied to all clusters simultaneously, this alternative method of AGN correction results in an inferred (sSFR) $= 5.0^{+1.0}_{-0.5} \times 10^{-11}$ yr$^{-1}$ among the clusters without measurable substructure but no measurable change in A3128. In this example, uncorrected AGN contamination would dominate the observed difference in (sSFR), and we would overestimate the potential impact of pre-processing in the group environment.

### 6.6. MIR Butcher–Oemler Effect

The relative importance of gas starvation and RPS is also probed by the evolution in (SFR) as a function of cosmic time. The classic example of this is the Butcher–Oemler effect (Butcher & Oemler 1978). Haines et al. (2009) constructed an analogous measurement with SFRs measured via $\nu L_{\nu}$ (24 $\mu$m) among the LoCuSS cluster galaxies. They employed a SFR threshold of $8.6 M_\odot$ yr$^{-1}$ (Salpeter IMF), and they found that $f_{\text{SF}} \propto (1+z)^n$ with $n = 5.7^{+2.1}_{-1.6}$. However, the fit to the LoCuSS clusters systematically overpredicts $f_{\text{SF}}$ in the Saintonge et al. (2008) clusters, despite the lower SFR threshold ($5 M_\odot$ yr$^{-1}$) used by Saintonge et al. (2008). Figure 12 shows their fit to $f_{\text{SF}}$ among the LoCuSS clusters as a function of redshift. The $f_{\text{SF}}$ values for our clusters and for a higher redshift cluster sample measured by Saintonge et al. (2008) are superimposed. The eight clusters in our sample, shown as the red triangles in Figure 12, are clearly consistent with the Haines et al. (2009) result within the uncertainties, provided that we convert the SFR threshold used by Haines et al. (2009) to the scaled Salpeter IMF.

One possible explanation for the disagreement between Haines et al. (2009) and Saintonge et al. (2008) is the different AGN correction methods they employed. Haines et al. (2009) required very strict criteria to identify and eliminate AGNs in their sample, while Saintonge et al. (2008) used less restrictive criteria based on X-ray luminosity. X-ray selection of AGNs identifies many cluster AGNs that do not appear in a BPT diagram (e.g., Martini et al. 2006), which would tend to reduce the number of MIR-luminous galaxies in the Saintonge et al. (2008) results compared to what they would have found with methods identical to Haines et al. (2009).

In Section 6.5, we considered the impact of X-ray-only AGN identification on the inferred (sSFR). This becomes a more important consideration at high $z$, because the frequency of luminous AGNs increases dramatically with redshift (Martini et al. 2009). Figure 12 also includes two points for each cluster in our sample. One shows $f_{\text{SF}}$ with the IR AGN selection included (filled triangles) and the other shows $f_{\text{SF}}$ that we would measure if we only knew about the X-ray-selected AGNs (open triangles). The $f_{\text{SF}}$ inferred from the X-ray-only selection in AC114 differs by 1.6$\sigma$ from the result when the full AGN sample is considered. This illustrates the contamination that X-ray-only AGN identification can introduce to integrated SFRs. This contamination becomes more severe, and appears in other clusters, for SFR thresholds less than the fairly high value employed by Haines et al. (2009).

### 7. DISCUSSION

In Sections 6.1 and 6.3 we examined correlations between environment, SFR and $M_\star$. We found a strong correlation of (SFR) with $R/R_{200}$ and a correlation between SFR and $M_\star$ among SFGs. We also found evidence for a transition population of low-SFR galaxies near the cluster center. We interpret this...
population as evidence that galaxies in this region experience a rapid reduction in SFRs that initiates their transition from SFGs to passive galaxies. This interpretation was supported by a possible trend toward larger $L/TIR$ farther out in the cluster (Section 6.4). We also found evidence for a concentration of massive galaxies near the cluster center (Section 6.2).

In this section, we consider the results of Sections 6.3–6.5 in more detail and interpret them in the context of competing mechanisms to end star formation in cluster galaxies (Section 7.1). We also briefly discuss the additional information that the Butcher–Oemler effect can provide about the impact of the cluster environment on SFGs (Section 7.2).

### 7.1. Star Formation in Clusters

In Section 6, we examined several diagnostics for the impact of the cluster environment on star formation. These include partial correlation analysis, (SFR) versus radius, and an examination of TIR LFs. One important result was the presence of a positive partial correlation between SFR and $M_*$ at fixed $R/R_\text{200}$. This implies that more massive galaxies can more easily resist the process that regulates star formation among cluster galaxies.

There is disagreement in the literature concerning the importance of different mechanisms to shut down star formation in clusters. For example, Simard et al. (2009) determined that evolution in cluster SFRs is controlled by galaxy–galaxy interactions because the growth in the fractions of early-type and passive galaxies track one another very closely in their sample. This contrasts with the results of Moran et al. (2007), who concluded that changes in SFR and morphology in cluster galaxies occur independently and that only morphological changes are controlled primarily by galaxy–galaxy interactions. Two hydrodynamic processes (RPS and gas starvation) are commonly suggested as mechanisms for galaxy–ICM interactions, but only RPS has been directly observed to work in nearby clusters (Kenney et al. 2004; Sivanandam et al. 2010). We therefore ask whether our observations are consistent with RPS alone or if an additional mechanism is required to explain the observations.

Treu et al. (2003) determined that RPS works effectively for Milky Way-like galaxies in a cluster with $M_{\text{vir}} = 8 \times 10^{14} M_\odot$ when $R < 0.5 R_{\text{200}}$. Our sample is restricted to projected $R < 0.4 R_{\text{200}}$, and their cluster mass is similar to the typical cluster in our sample ($M_{\text{200, last}} \approx 5 \times 10^{14} M_\odot$), so RPS should act efficiently on most galaxies in our sample. Nevertheless, some of our observations are inconsistent with the assumption that RPS on cold gas is the only mechanism necessary to regulate star formation in cluster galaxies. First, the best-fit power law to the SFR–radius relation is consistent—within large observational uncertainties—with a model that removes only galaxies’ hot gas as they enter a cluster (Figure 8). In addition, we found in Section 6.4 that the TIR LF of the combined cluster sample is significantly better fitted by a Schechter function with variable $L/TIR$ than by a redshift-appropriate field galaxy LF, but the simplest prediction of RPS suggests that the SFG population in clusters should be well described by the field galaxy LF (Bai et al. 2006, 2009). However, we note that Cortese et al. (2008) found that the presence of massive, red galaxies can strongly influence the UV LF in clusters without the need for a strong environmental effect. This effect is especially important for the faint-end slope of the UV LF. Because Cortese et al. (2008) selected their SFGs based on NUV $- r$, which is more closely related to sSFR than to SFR, the effect of massive galaxies they identified in their sample is unlikely to contribute to the population of SFR-selected galaxies we examine. We therefore expect that any differences in the shape of the TIR LF compared to the field would imply the presence of a population of SFGs in transition.

To interpret the disagreement between the field LF and the LF of the merged cluster sample, we need to know whether it results from different faint-end slopes between the cluster population and the field, different $L/TIR$, or some combination of the two. This level of detail is impossible given the completeness limit in the present sample. Furthermore, any systematic errors in our completeness corrections (e.g., a missing color term) would affect the shape of the LF. The implications of the poor agreement between the cluster and field LFs are therefore ambiguous.

In addition to the evidence that gas starvation acts on galaxy cluster members, we also found evidence that RPS contributes significantly to the decline of SFRs among cluster galaxies. Figure 8 shows that the dependence of SFR on $R/R_{\text{200}}$ is driven largely by a decline in $f_{\text{TIR}}$ toward the cluster center, and only a small fraction of the dependence is driven by a decline in the SFRs of individual SFGs. This is more consistent with RPS than with gas starvation. We also found a positive correlation between SFR and $M_*$ among SFGs, which would be expected if RPS played a dominant role in regulating SFRs of cluster galaxies. Furthermore, the residual decline in (SFR)$_{\text{TIR}}$ with $R/R_{\text{200}}$ does not occur smoothly, but appears to set in rapidly at $R \approx 0.1 R_{\text{200}}$. The crossing time for this region ($\sim 100$ Myr) is consistent with RPS as the origin of the transition, but the small size of this region compared to the radius where RPS is theoretically expected to be important ($0.5 R_{\text{200}}$) is surprising. This explanation is also difficult to reconcile with the smooth decline in $f_{\text{TIR}}$ across all radii, which we attribute to RPS.

To interpret Figures 8 and 11, we must consider projection effects and the influence of galaxy “backsplash.” Backsplash refers to galaxies on nearly radial orbits that pass through the dense central region of the cluster and return to large $R/R_{\text{200}}$. Projection effects will cause some galaxies at intrinsically large $R/R_{\text{200}}$ to appear at small radii when the cluster is projected onto the plane of the sky. Backsplash can make radial gradients like the ones shown in Figure 8 particularly difficult to interpret, because even galaxies presently at large radii may have passed near the cluster center in the past. Gill et al. (2005) use N-body simulations to find that 50% of galaxies between 1–2 $R_{\text{200}}$ are backsplash galaxies, and 90% of these have been inside $0.5 R_{\text{200}}$ at some point in the past. Pimbblet (2011) uses mixture modeling with observations of real clusters from SDSS to infer that 60% ± 6% of galaxies at $R/R_{\text{200}} = 0.3$ are part of the backsplash population, so they were even closer the dense cluster core at some point in the past. Galaxies on radial orbits in a cluster with an $R^{-2}$ mass profile and a core radius of 0.05 $R_{\text{200}}$ spend only 4% of their time inside 0.1 $R_{\text{200}}$ and only 32% of their time inside 0.5 $R_{\text{200}}$. The assumption of radial orbits in a cluster with an $R^{-2}$ density profile also implies that approximately half of the galaxies in an isolated cluster with an age of 8 Gyr have previously passed through the cluster center. As a result, the dynamic nature of the cluster populations means the dependence of star formation on projected radius relative to the underlying, three-dimensional trends. Again, this suggests that the projected trends shown in Figure 8 are lower limits to the true, three-dimensional trends.

The effects of projection are potentially equally important. For an $R^{-2}$ galaxy density profile, $\sim 40\%$ of galaxies with projected $R < 0.1 R_{\text{200}}$ actually reside outside 0.1 $R_{\text{200}}$. The
trend in $SFR$ versus radius (Figure 8) implies that at least 67% of SFGs that appear with $R < 0.1\ R_{200}$ in projection are likely to have three-dimensional radii outside this limit. If we extrapolate the trend in Figure 8 to $R_{200}$, we can infer that 20% of SFGs with projected $R < 0.4\ R_{200}$ have three-dimensional radii outside this region. Furthermore, this represents an upper limit, since Figure 8 includes projection effects. Therefore, we cannot assume that SFGs at small $R/R_{200}$ actually reside in the high-density regions where RPS is most important. This suggests that SFGs that physically reside inside 0.1\ $R_{200}$ have their SFRs reduced more drastically than implied by Figure 8.

The steep dependence of $SFR$ on radius therefore works to minimize apparent radial trends seen among the SFG population in projection, which could lead to the small dependence of $\langle SFR \rangle_{SFG}$ on $R/R_{200}$. This suggests that the sharp drop in $\langle SFR \rangle_{SFG}$ at projected radius 0.1\ $R_{200}$ would be stronger if measured relative to physical radius rather than in projection.

An ideal way to account for both projection and backslash is to compare our results to model predictions that include these effects. This approach allows more reliable conclusions than simple, ad hoc arguments. Book & Benson (2010) developed a model for the removal of hot gas from galaxies by the ICM, which is the physical mechanism that drives gas starvation. Their “shocks” model predicts that galaxies that experience this process should show $SFR \propto (R/R_{200})^{-0.6}$ between 0.1–0.4\ $R_{200}$ (their Figure 3). This is consistent with our results in Section 6.3 ($SFR \propto (R/R_{200})^{1.3\pm 0.7}$). However, the model yields overall poor agreement with the data, even after we fit the normalization of the model to best match the observations. This contrasts with the results of Book & Benson (2010), who found that their model agrees well with the SFR–radius relation measured among the Canadian Network for Observation Cosmology survey clusters (Balogh et al. 2000). The resolution of this conflict will require additional observations and more sophisticated theoretical models that provide predictions for competing processes.

The large statistical uncertainties on the measured SFR versus $R/R_{200}$ preclude detailed comparisons between our observations and a model for either RPS or gas starvation, so we must rely on qualitative arguments. Figure 10 demonstrates that the field galaxy TIR LF at the median redshift of the combined cluster galaxy sample provides a poor match to the observed TIR LF, and this discrepancy is most pronounced among galaxies with the lowest SFRs. The bottom panel of Figure 8 also shows a sudden decrease in the SFRs of SFGs with projected radii $R < 0.1\ R_{200}$. The crossing time for this region is $\sim 200\ Myr$, which suggests that RPS is responsible for this reduction. However, only 5% of SFGs in the cluster have $R < 0.1\ R_{200}$, so this reduction in the SFRs of SFGs near the cluster center cannot account for the discrepancy between the TIR LFs of cluster and field galaxies. If the disagreement between the cluster and field LFs is physical and does not result from systematic errors, there must also be an effect on SFGs at larger radii that is not apparent in the present sample. The entire sample has $R < 0.5\ R_{200}$, so either RPS or gas starvation could plausibly be responsible.

Bai et al. (2009) found that the TIR LFs of many clusters are consistent with one another and with the field LF. They inferred that cluster galaxies only rarely occupy a transition phase between SFRs characteristic of field galaxies and complete passivity. From this, they determined that star formation in cluster galaxies must be truncated on short timescales compared to the lifetime of the cluster. Both we and Bai et al. (2006) find $\sim 1\sigma$ variations in the shape of the TIR LF in different $R/R_{200}$ bins. The observed decreases in $L_{\text{TIR}}^{*}$, while not statistically significant, are consistent with the decline in $(SFR)_{SFG}$ for $R < 0.1\ R_{200}$ (Figure 8). The latter result implies that the high ICM density near cluster centers reduces SFRs in individual SFGs. The smooth decline in $SFR$ as a function of $R/R_{200}$ suggests that this process eventually results in the end of star formation in these galaxies. Projection effects and backslash will alter the observed trends from the intrinsic three-dimensional trends. Both effects would cause the projected trends to appear weaker than the true, three-dimensional variations in the cluster. This suggests that the observed radial variations are real, and the trends with projected radius likely underestimate the intrinsic, three-dimensional trends.

We find lower $(SFR)_{SFG}$ inside 0.1\ $R_{200}$ compared to outside this radius. We also see hints of this change in the lower $L_{\text{TIR}}^{*}$ near the cluster center compared to further out. The variation in the properties of SFGs implied by these measurements indicates a substantial change in the SFGs very close to the cluster center. The crossing time for the sphere with radius 0.1\ $R_{200}$ is less than 200\ Myr, which strongly favors RPS as an explanation. However, we also see indications for a deficit in the number of low-SFR cluster galaxies relative to the field population. Because only $\sim 5\%$ of SFGs have projected $R < 0.1\ R_{200}$, galaxies outside 0.1\ $R_{200}$ must dominate the underabundance of galaxies with $SFR \approx 3\ M_\odot\ yr^{-1}$.

We can determine which processes are more likely to be responsible for the deficit from the time required to make the transition. We find that 66% of SFGs with $M_R < -20$ mag have $L_{\text{TIR}} < L_{\text{TIR}}^{*}$, where $L_{\text{TIR}}^{*}$ is the luminosity expected for a typical field spiral with $M_R = -20$. If 50% of field SFGs with the same $M_R$ distribution had $L_{\text{TIR}} < L_{\text{TIR}}^{*}$, then 16% of cluster SFGs would be in transition. Combined with the gas consumption timescale of a typical spiral galaxy (2.4\ Gyr; Bigiel et al. 2011), this would imply a transition time of $\sim 400$\ Myr. This timescale is approximately twice the orbital time for a star in an ordinary spiral galaxy, and it is consistent with, but slightly longer than, the 100\ Myr timescale for RPS predicted by Kapferer et al. (2009). However, the assumption that 50% of field SFGs in an $M_R$-matched sample would have $L_{\text{TIR}} < L_{\text{TIR}}^{*}$ is arbitrary. A comparison of the SFR–$M_R$ relations in clusters and in the field is required to measure the transition time more precisely.

If star formation in most cluster galaxies ends as a result of RPS, post-starburst galaxies should be more frequent in clusters than in the field. This is a robust prediction of any scenario that results in a rapid transition of SFGs to passive evolution. Galaxies with K+A spectra, which are usually associated with post-starburst populations, should remain visible for $\sim 100$\ Myr to 1\ Gyr. This is short compared to the cluster crossing time, so a large population of K+A galaxies relative to SFGs would be strong evidence that RPS plays an important role. Dressler et al. (1999) found that the fraction of K+A galaxies is much higher in clusters than in the field. However, von der Linden et al. (2010) found no dependence of the ratio of $N_{K+A}/N_{SFG}$ on $R/R_{200}$, and Yan et al. (2009) report that galaxies with K+A spectra are less common in overdense environments like clusters than in the field at $z \approx 0.1$. They suggest that K+A galaxies appear at constant absolute density, and that this density corresponds to the group scale at $z \approx 0$. These authors use different methods to select their K+A samples: Dressler et al. (1999) rely on $[O\ II]$ to exclude SFGs. Yan et al. (2009) use H$\beta$, and von der Linden et al. (2010) select galaxies with excess Balmer line absorption
from their principal component analysis. This may account for the apparent contradictions in their results, but the different conclusions preclude the use of K+A galaxies to test the impact of RPS on cluster galaxies.

If pre-processing in groups substantially affects the star formation histories of cluster galaxies, it would provide strong evidence in favor of slow processes like gas starvation. Groups that have recently fallen into a cluster might appear as an excess in the substructure parameter (Dressler & Shectman 1988). In our sample only A3125 has a mass comparable to galaxy groups, and we have not considered that cluster in our analysis. Therefore, we cannot directly constrain the mechanism that drives SFR evolution in group members. However, we find that (sSFR) is higher among clusters with no substructure than in A3128, which is the only member of our main sample with significant substructure. This could indicate that galaxies that have recently been part of groups have experienced pre-processing, but it could also arise from cosmic variance. In a recent study of SDSS galaxy clusters, von der Linden et al. (2010) found a trend of SFR with radius that extended to 2 R200. They concluded that pre-processing of galaxies before they become cluster members is likely to contribute significantly to the SFR–radius relation.

7.2. Evolution

In Section 6.6 we suggested that the evolution of star formation in clusters is sensitive to the mechanism(s) responsible for the appearance of the z = 0 SFR–density relation. In particular, the rate of evolution of fSF is sensitive to the operation of the cluster environment on recently accreted field galaxies. Figure 12 shows the fraction of SFGs in clusters as a function of redshift since z ≈ 0.8 for the clusters in our sample (red) compared to the samples of Saintonge et al. (2008) and Haines et al. (2009).

We use measurements of fSF versus z to estimate the time required for fSF in clusters to decline by a factor of e compared to coeval field galaxies. The best fit to the Haines et al. (2009) galaxies (fSF ∝ (1 + z)^m, m = 5.7 ± 2.1) is shown as the black line in Figure 12, and it agrees well with the clusters in our sample. Le Floc’h et al. (2005) report that the field galaxy LF of star formation in clusters to decline by a factor of e compared to coeval field galaxies. The threshold we use to identify SFGs (SFR > 6.0 M⊙ yr⁻¹ for a scaled Salpeter IMF) is larger than the SFR that corresponds to L^TIR (2.8 M⊙ yr⁻¹), so we assume that fSF among field galaxies has the same redshift dependence as L^TIR. With this assumption, we can measure the relative change in fSF as a function of redshift and determine how the cluster environment induces SFGs to turn passive. The ratio of fSF,clust to fSF,field has undergone approximately 1.7 ± 1.2 e-foldings since z = 1. The elapsed time over this redshift interval is 7.7 Gyr, so the e-folding time for fSF,clust/fSF,field is 4.6^+1.8 Gyr.

The e-folding time of fSF does not correspond directly to the truncation time for star formation in individual cluster members. New SFGs constantly fall into the cluster from the field, and this results in a longer timescale for fSF,clust/fSF,field to decline than for SFRs to decline in individual galaxies. The rate at which SFGs fall into the cluster combines with the timescale for the conversion of individual SFGs to passive evolution to determine how rapidly fSF,clust/fSF,field changes. The timescale for this change is long compared to the gas exhaustion time in typical spiral galaxies (2.4 Gyr; Bigiel et al. 2011), but this does not necessarily indicate that the timescale for the evolution of individual SFGs is similarly long, because the rate at which clusters accrete SFGs evolves with redshift. If the timescale for evolution of individual SFGs is indeed long, it would favor gas starvation over RPS as the primary mechanism to end star formation in cluster galaxies.

In addition to the degeneracy between changes in infall and the timescale for individual SFGs to stop forming stars, the measured timescale for fSF,clust/fSF,field to evolve includes significant observational uncertainty. The Haines et al. (2009) best fit overpredicts fSF among the high-z clusters, despite the higher SFR threshold employed by Haines et al. (2009), so it underestimates the timescale over which fSF,clust/fSF,field evolves. Additional observations are required to correct this bias. A measurement of fSF versus z with a longer redshift baseline and consistent identification of SFGs will appear in our next paper.

8. SUMMARY AND CONCLUSIONS

We have used visible to MIR observations of eight low-z galaxy clusters to constrain the impact of the cluster environment on star formation. We examined the relationship between star formation and environment among cluster members and found a positive partial correlation of SFR with M* among SFGs. We also found a trend for larger SFR with R/R200 when we include passive galaxies (fSF ∝ (R/R200)1.1±0.3). This simple power law provides a good match to the data. Book & Benson (2010) model the impact of stripping hot gas on star formation in cluster galaxies. Their model is marginally consistent with the power law that best fits the observed SFR–radius relation, but it is a poor match to the data themselves. The (SFR)–R/R200 relation is dominated by a decline in the fraction of SFGs toward the cluster center, but we also find lower (SFR) among SFGs with projected R < 0.1 R200. The dominance of the decline in fSF and the short crossing time of a sphere with radius 0.1 R200 both suggest that RPS contributes significantly to the observed trend in SFR with R/R200, as does the positive correlation of SFR with M*, among SFGs. Projections effects and backsplash both work to weaken the observed trends relative to the intrinsic variation in three dimensions, which can hide the steep gradients that would be expected from RPS.

We also examined the relationship between R/R200 and stellar mass in cluster galaxies. We found that galaxies with R < 0.1 R200 show larger (M*) than galaxies farther out in the cluster, even after we have eliminated BCGs from our sample. This excess is significant at ∼3.5σ, and projection effects are also expected to weaken the observed trend relative to the intrinsic, three-dimensional variation, so we conclude that it is robust. Von der Linden et al. (2010) found no such excess once they had removed BCGs, so our result conflicts with theirs. This difference may result from the SDSS fiber collisions. Our sample is limited to galaxies more luminous than the SDSS r-band magnitude limit at the median redshift of the von der Linden et al. (2010) cluster sample, so our sample is on average more massive than theirs. The timescale for dynamical friction to affect the cluster as a whole is much longer than the Hubble time. However, the expected relaxation time inside 0.1 R200 is only ∼200 Myr. This suggests that cluster galaxies undergo mass segregation via virial relaxation, analogous to the mass segregation exhibited by some Galactic globular clusters, which leads to an increase in the average stellar mass of galaxies near the cluster center.
We measured the fractions of SFGs in our cluster sample as a function of redshift, and we found that these fractions are consistent with the measurements made by Haines et al. (2009) for the LoCuSS clusters. However, incomplete AGN subtraction can introduce significant contamination to the integrated star formation in galaxy clusters. For example, we found that eliminating only X-ray AGNs from the sample prior to calculating $f_{\text{SF}}$ results in a $\sim 1\sigma$ excess in AC114 in Figure 12. The consequences are both more significant and more widespread for lower SFR thresholds, because low-luminosity AGNs are much more common. This can bias measurements of star formation as a function of redshift, since the AGN contribution is expected to be more significant at higher redshift (Martini et al. 2009). With a long enough redshift baseline, evolution in $f_{\text{SF}}$ with cosmic time can probe the timescale for the end of star formation in cluster galaxies.

Our measurements are most consistent with RPS as the primary mechanism to reduce star formation in cluster galaxies. The SFR–radius relation agrees better with the predictions of RPS than with gas starvation over the range of radii that we study. The positive correlation of SFR with $M_c$, among cluster members and is more consistent with gas starvation. A measurement of the rate among cluster members and is more consistent with gas starvation. A measurement of the rate

thermore, Bai et al. (2009) also found that the luminous end of the SFR dominates the reduction of SFR among cluster galaxies. Furthermore, Bai et al. (2009) also found that the luminous end of the TIR LF does not vary significantly between $z = 0$ and $z = 0$ clusters, and we similarly find that the redshift-appropriate field galaxy LF provides a good match to the observed TIR LF in each cluster. While this is also consistent with RPS as the primary mechanism to end star formation among cluster galaxies, the disagreement between the field galaxy LF and the combined cluster sample suggests that there are small deviations between the individual clusters and the field galaxy LFs that we overlook due to limited precision in the measured LFs. Such deviations would not be consistent with RPS, but these deviations might also result from systematic errors in our completeness corrections.

By contrast, the long timescale we infer for the evolution of $f_{\text{SF}}$ conflicts with the conclusion that RPS ends star formation among cluster members and is more consistent with gas starvation. This agrees with the conclusions of Verdugo et al. (2008) and von der Linden et al. (2010), who found independent evidence in favor of gas starvation. A measurement of the rate of change in $f_{\text{SF}}$ as a function of redshift can provide an additional line of evidence to help resolve this disagreement. Present results favor a long timescale, but these include significant systematic uncertainties. A measurement with a single sample of uniformly analyzed clusters will be the subject of a future paper.

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oratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

APPENDIX

ASYMMETRIC DISTRIBUTION FUNCTION

In order to apply the method described in Section 5 to construct an LF, we must smoothly distribute the weight of a galaxy across the specified luminosity bins. The method described in Section 5.1 to calculate $L_{\text{TIR}}$ produces asymmetric uncertainties, $L_{\text{TIR}} = \mu - \sigma$, so we need an asymmetric PDF to distribute weights correctly. This PDF must reduce to the normal distribution in the case when the upper and lower luminosity uncertainties are equal (i.e., Gaussian errors). Here, we describe a piecewise smooth function that satisfies these requirements.

First, we define an effective dispersion $\sigma_e = \sqrt{\sigma_u \sigma_l}$, where $\sigma_u$ and $\sigma_l$ are the upper and lower uncertainties on $L_{\text{TIR}}$, respectively. We then define an alternative dispersion, $\sigma(L)$, which describes the instantaneous shape of the PDF at a luminosity $L$,

$$\sigma(L) = \begin{cases} \sigma_l & \text{if } L < \mu - \sigma_u \\ \sigma_e + (\sigma_e - \sigma_l) \frac{|L - \mu|}{\sigma_u} & \text{if } \mu - \sigma_u \leq L < \mu \\ \sigma_l & \text{if } L = \mu \\ \sigma_u & \text{if } L < \mu \leq \mu + \sigma_u \\ \sigma_e + (\sigma_e - \sigma_u) \frac{|L - \mu|}{\sigma_u} & \text{if } \mu + \sigma_u < L, \end{cases}$$

where $\mu$ is the best estimate of $L_{\text{TIR}}$, $\sigma_u$ and $\sigma_l$ are the upper and lower uncertainties on $\mu$, respectively. $\sigma(L)$ smoothly connects the low-$L$ and high-$L$ tails of the desired distribution function. Given $\sigma(L)$, we can calculate the probability density for a galaxy with measured luminosity $\mu$ at $L$. This probability density is given by

$$f(L, \mu, \sigma_u, \sigma_l) = \frac{1}{\sqrt{2\pi} \sigma(L)} e^{-((L-\mu)^2/2\sigma^2(L))},$$

where $\sigma(L)$ is given by Equation (A1).

The PDF described by Equations (A1) and (A2) approaches Gaussian at the high- and low-$L$ extremes, with dispersions $\sigma_u$ and $\sigma_l$, respectively. It also smoothly connects these two limiting cases, integrates to unity, and has dispersion equal to the geometric mean of $\sigma_u$ and $\sigma_l$ at the nominal luminosity. It therefore gives a PDF for the luminosity of a given galaxy that satisfies our requirements and that is consistent with the available information about $L_{\text{TIR}}$.

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