SPITZER/MIPS 24 µm OBSERVATIONS OF GALAXY CLUSTERS: AN INCREASING FRACTION OF OBSCURED STAR-FORMING MEMBERS FROM $z = 0.02$ TO $z = 0.83$

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ABSTRACT

We study the mid-infrared properties of 1315 spectroscopically confirmed members in eight massive ($M_{\mathrm{vir}} \geq 5 \times 10^{14} M_{\odot}$) galaxy clusters covering the redshift range from 0.02 to 0.83. The selected clusters all have deep Spitzer/MIPS 24 µm observations, Hubble and ground-based photometry, and extensive redshift catalogs. We observe for the first time an increase in the fraction of cluster galaxies with mid-infrared star formation rates higher than $5 M_{\odot} \text{yr}^{-1}$ from $3\%$ at $z = 0.02$ to $13\%$ at $z = 0.83$ ($R_p \leq 1$ Mpc). This increase is reproduced even when considering only the most massive members ($M_\ast \geq 4 \times 10^{10} M_{\odot}$). The 24 µm observations reveal stronger evolution in the fraction of blue/star-forming cluster galaxies than in color-selected samples: the number of dusty, strongly star-forming cluster galaxies increases with redshift, and combining these with the optically defined Butcher-Oemler members [$\Delta(B - V) < -0.2$] doubles the total fraction of blue/star-forming galaxies in the inner Mpc of the clusters to $\sim 23\%$ at $z = 0.83$. These results, the first of our Spitzer/MIPS InfraRed Cluster Survey (SMIRCS), support earlier studies indicating that the increase in star-forming members is driven by cluster assembly and galaxy infall, as is expected in the framework of hierarchical formation.

Subject headings: galaxies: clusters: general — galaxies: evolution — galaxies: fundamental parameters

Online material: color figure

1. INTRODUCTION

Butcher & Oemler (1978, 1984) observed that galaxy clusters at intermediate redshift have a higher fraction of members with blue optical colors than clusters in the local universe, thus providing a key piece of evidence supporting galaxy evolution. This increase in blue members with redshift, named the Butcher-Oemler (BO) effect, was intensely debated for 2 decades (e.g., Mathieu & Spinrad 1981; Dressler & Gunn 1982). However, multiple optical studies based on spectroscopic observations have since confirmed the increase in blue, star-forming galaxies in higher redshift clusters (e.g., Couch & Sharples 1987; Caldwell & Rose 1997; Fisher et al. 1998; Ellingson et al. 2001) and found that BO galaxies reveal signs of recent and ongoing star formation. The paramount question now is have we seen only the tip of the iceberg?

Most studies of star-forming galaxies in clusters rely on rest-frame ultraviolet or optical tracers (e.g., Balogh et al. 1998; Poggianti et al. 2006), but UV/optical tracers can suffer severely from dust obscuration, especially when star formation (SF) is concentrated in the nuclear regions (Kennicutt 1998). For example, ultraluminous infrared galaxies have SF rates of $\geq 1000 \ M_{\odot} \text{yr}^{-1}$, yet many ULIRGs fail to even be detected at UV and optical wavelengths (e.g., Houck et al. 2005). Although corrections for dust attenuation are possible, reliable estimates of SF rates cannot be achieved solely using rest-frame UV/optical observations (Bell 2002; Cardiel et al. 2003).

A substantially more robust method of determining total SF rates is with mid-infrared (MIR) imaging. The first MIR imaging of galaxy clusters at intermediate redshifts was taken with ISO’s ISOCAM camera, and Duc et al. (2002) found that at least 90% of the star formation was hidden at optical wavelengths. The first handful of galaxy clusters observed with the MIPS camera on the Spitzer Space Telescope (SST) have also revealed strong dust-obscured star formation (Geach et al. 2006; Marcillac et al. 2007; Bai et al. 2007).

It remains unclear as to what causes the increase in star-forming galaxy cluster members. Detailed morphological studies of blue galaxies [defined as having $\Delta(B - V) < -0.2$] with the Hubble Space Telescope (HST) find that most are disk systems similar to those in local clusters (e.g., Dressler et al. 1994; Couch et al. 1994); past studies also find that many show signs of interactions or mergers (Lavery & Henry 1988; Lavery et al. 1992; Couch et al. 1994; Oemler et al. 1997). More recently, studies indicate that galaxy infall is a viable explanation for the significant numbers of blue galaxies and their disturbed morphologies in intermediate-redshift clusters (e.g., van Dokkum et al. 1998b; Ellingson et al. 2001; Tran et al. 2005), a scenario supported by hierarchical clustering models (Kauffmann 1995). In this case, galaxy clusters that are accreting a significant number of new members should have a higher fraction of star-forming galaxies, especially at higher redshifts when the amount of activity was enhanced also in the field.

Here we present the first comprehensive study of SST/MIPS 24 µm imaging of galaxies that are spectroscopically confirmed members of eight massive ($M_{\mathrm{vir}} \geq 5 \times 10^{14} M_{\odot}$) X-ray-luminous clusters spanning a wide redshift range ($0.02 < z < 0.83$). After presenting the data in § 2, we focus our analysis in § 3 and § 4 on the evolution of star-forming members with redshift. A cosmology with $(\Omega_m, \Omega_\Lambda) = (0.7, 0.3)$ is assumed throughout the Letter; at $z = 0.83$, the look-back time is $\sim 7$ Gyr.

2. DATA

We have assembled a data set of eight galaxy clusters at $0.02 \leq z \leq 0.83$ that have a total of 1315 spectroscopically confirmed members. The core of our sample is composed of five clusters spanning the entire redshift range with large spectroscopic membership, uniform multifilter optical photometry, and deep SST/MIPS imaging. For the part of the analysis that does not intersect with the SMIRCS clusters, we added two additional clusters with similar spectroscopic and photometric properties. A full discussion of the selection criteria and pipeline is presented in the online supplementary material.

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3. $\Delta(B - V)$ is the color offset from the red sequence fit to the cluster ellipticals.
4. This work is based on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA.
not depend on rest-frame \((B - V)\) color, we fold into the sample three additional clusters: A1689 for which \(M\) IR data from ISO-CAM is available (Duc et al. 2002), and CL 0024 and MS 0451, both of which have extensive redshift catalogs (Moran et al. 2005) and MIPS observations. Observational details for all clusters are in Table 1.

### 2.1. Optical Photometry and Spectroscopy

The optical photometry for the five main clusters is from Holden et al. (2007, hereafter H07), where magnitudes and colors were derived from Sersic models fitted to HST/WFC2 images (MS 1358, MS 2053, and RX J0152), HST/ACS images (MS 1054), and SDSS mosaics for Coma. The conversion to rest-frame values is done by interpolating between the passbands (Blakeslee et al. 2006) and has errors of \(\pm 0.02\) mag. The mass-to-light ratios (\(M/L_{B}\)) and stellar masses were calculated using the relation between rest-frame \((B - V)\) color and \(M/L_{B}\), see H07 for details and a discussion on the associated errors.

### 2.2. MIPS 24 \(\mu m\) Imaging

All MIPS data sets were retrieved from the Spitzer public archive. Individual frames were corrected with scan mirror position-dependent flats and then mosaicked with the MOPEX software (Makovoz & Khan 2005) to a pixel size of 1.2". Integration times \(t_{\text{int}}\) and background levels \(F_{\text{bg}}\) in these mosaics are given in Table 1. Photometry was performed with APEX (Makovoz & Marleau 2005) using a 3" diameter aperture and an aperture correction of 9.49 as given in the MIPS data handbook. A small aperture is necessary to avoid contamination in the deep and crowded cluster fields. The fluxes are consistent with results from PSF-fitting photometry with scatter from a 1:1 relation in the range of 15–25 \(\mu\)Jy.

To estimate the completeness of each MIPS catalog, we added to the mosaics artificial sources modeled on the PSF. To avoid overcrowding, we simulated 30 signals at once and repeated the process 30 times for each cluster (the 50% completeness limits, \(F_{\text{50\%}}\), are presented in Table 1). Finally, the MIPS sources were matched with the optical catalogs using a 2" search radius (Bai et al. 2007). From randomization of the MIPS coordinates, we estimate the rate of false identification to be \(7\% \pm 4\%\), and little dependency of this error rate on redshift or color is observed.

### 3. RESULTS

#### 3.1. Color-Magnitude Diagrams

Figure 1 presents the color-magnitude diagrams of the five main clusters with photometry from H07. Because the MIPS sensitivity varies from cluster to cluster, we apply a SF rate limit of \(5 M_{\odot} \text{yr}^{-1}\). The first immediate observation is that the number

| Name            | Coordinates (R.A., Decl.) (J2000.0) | \(z\) Range\(^a\) | \(L_{\text{IR}}\) \((10^{11} \text{ergs s}^{-1})\) | \(N_{1}\) | \(N_{2}\) \(^b\) | \(N_{3}\) \(^c\) | \(t_{\text{int}}\) \((\text{s pixel}^{-1})\) | \(F_{\text{8–1000 \mu m}}\) \((\text{MJy sr}^{-1})\) | \(F_{\text{100\%}}\) \((\text{MJy sr}^{-1})\) |
|-----------------|-------------------------------------|-----------------|-----------------|-------|---------|---------|----------------|----------------|----------------|
| Coma            | 12 59 35.7, +27 57 34               | 0.013–0.033     | 9.0 ± 0.2       | 244   | 63      | 134     | 73             | 32.8            | 0.02            |
| A1689           | 11 31 25.9, −01 20 17               | 0.17–0.22       | 21.4 ± 1.0      | 81    | 52      | 12      | 2(2)           | 2700            | 20.6            |
| MS 1358+62      | 13 59 50.4, +62 31 03               | 0.315–0.342     | 10.2 ± 0.7      | 171   | 73      | 21      | 3              | 2700            | 20.6            |
| CL 0024+17      | 00 26 35.7, +17 09 43               | 0.373–0.402     | 2.9 ± 0.1       | 205   | 51      | 11      | 6(11)         | 2700            | 24.5            |
| MS 0451−03      | 04 54 10.9, −03 01 07               | 0.52–0.86       | 21.0 ± 0.4      | 242   | 38      | 8       | 5(5)           | 2700            | 35.0            |
| MS 2053−04      | 20 56 21.3, −03 37 51               | 0.57–0.60       | 6.5 ± 0.4       | 85    | 43      | 15      | 8(4)           | 1950            | 35.2            |
| MS 1054−03      | 10 57 00.0, −03 37 36               | 0.80–0.86       | 16.4 ± 0.8      | 142   | 75      | 13      | 8(8)           | 3600            | 47.4            |
| RX J0152−13     | 01 52 43.9, −13 57 19               | 0.81–0.87       | 18.6 ± 1.9      | 147   | 61      | 19      | 8(8)           | 3600            | 31.9            |

\(^a\) Cluster members selected within this redshift range, as in H07 (Coma, MS 1358, MS 2053, MS 1054, RX J0152), Duc et al. 2002 (A1689), and Moran et al. 2007 (CL 0024 and MS 0451).

\(^b\) Bolometric X-ray luminosities from H07 (Coma, MS 1358, MS 2053, RX J0152), Bardeau et al. 2007 (A1689), Donahue et al. 1999 (MS 0451), and Zhang et al. 2005 (CL 0024).

\(^c\) Total number of spectroscopically confirmed members (magnitude-limited selection). Redshifts are taken from Beijersbergen 2003, Duc et al. 2002, Fisher et al. 1998, Moran et al. 2005, Moran et al. 2007, Tran et al. 2005, Tran et al. 2007, and Demarco et al. 2005, respectively.

\(^d\) Number of confirmed members within 1 Mpc of the cluster center and brighter than \(M_B = -19.5 + 5 \log h\).

\(^e\) Number of MIPS detections in the cluster; values in parentheses are the number of galaxies within \(N\), with SF rates \(\geq 5 M_{\odot} \text{yr}^{-1}\).

\(^f\) We are using ISOCAM mid-IR data from Duc et al. 2002 for A1689.

\(^g\) Over the central 3' × 3' of the MIPS image.
of strongly star-forming galaxies increases significantly with redshift. Using a field galaxy sample drawn from the same photometric and spectroscopic catalogs, we estimate a possible field contamination at \( z = 0.83 \) to be \( \sim 8\% \) (i.e., no more than one galaxy per cluster). In Figure 1, the dotted lines represent the original color criterion for BO galaxies. The ratio of the number of cluster galaxies with MIR SF rate \( \geq 5 \, M_\odot \, yr^{-1} \) above this color cut to the number of blue galaxies \( \Delta (B - V) < -0.2 \) increases with redshift.

### 3.2. The Mid-Infrared Butcher-Oemler Effect

For each cluster, we compute and plot in Figure 2 the fraction of confirmed star-forming cluster members after selecting by rest-frame \( B \)-band magnitude \( (M_B \leq -19.5) \), clustercentric distance,\(^6\) and MIR SF rate \( (\geq 5 \, M_\odot \, yr^{-1}) \). The errors on \( f_{\text{SF,MIPS}} \) represent the range that can be produced by taking the minimum and maximum conversion factors from \( F_{24 \, \mu m} \) to \( F_{1000 \, \mu m} \) instead of a single average value for each cluster and by varying the different selection thresholds by amounts comparable to the errors on each of these parameters.

Figure 2 shows that the fraction of galaxies in clusters with \( f_{\text{SF,MIPS}} \) steadily climbs from \( \sim 3\% \) locally to \( \sim 13\% \) at \( z = 0.83 \). Because H07 showed that a cluster’s morphological composition can vary depending on whether members are selected by mass or by luminosity, we apply an additional stellar mass cut of \( \log_{10}(M_*) \geq 10.6 \) (Fig. 3). The mass cut is applied only to the five main clusters for which uniform photometry and thus stellar masses are available; the remaining three clusters are shown only as upper limits. While the mass cut attenuates the increase in fraction of star-forming members, it does not completely suppress the trend. Thus, the MIR BO effect is not due to an increase in the fraction of faint, low-mass members temporarily brightened by strong star formation.

### 4. Discussion

Having established an increase in the fraction of MIR-detected galaxies from \( z \sim 0 \) to \( z \sim 0.83 \), we stress that optical studies are likely underestimating the increase in star-forming

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\(^6\) While the optical observations generally extend to \( R_e > 1.5 \) Mpc, the MIPS imaging for MS 1358 only extends to \( \sim 1 \) Mpc (\( \sim 50\%–60\% \) of \( r/200 \) for these clusters).
cluster galaxies with redshift. As seen in Figure 1, an increasing number of strong dust-obscured star-forming members appear on or near the red sequence at higher redshifts; these are not included in traditional color-selected BO studies. The late-type morphologies of these members support our interpretation of dusty star formation and red colors due to extinction (see also A901/902; Wolf et al. 2005).

Using the standard BO definition of $\Delta(B - V) < -0.2$, the fraction of blue galaxies with $M_p \leq -19.5$ and $R_p < 1$ Mpc at $z \sim 0.8$ is $\sim 11$%; however, including the red, massive, star-forming members raises the total fraction of blue/star-forming members to $\sim 23\%$. We note that for the five main clusters, the increase in the blue/star-forming fraction due to these red, star-forming members is $\{1.1, 1.2, 1.3, 1.7\}$ at $z = \{0.02, 0.33, 0.59, 0.83\}$; i.e., the relative importance of including red, dusty star-forming members increases with redshift.

Is this increase linked to galaxy infall? In Figure 2, both CL 0024 ($z \sim 0.4$) and MS 2053 ($z \sim 0.6$) are above the general trend established by the other six clusters. Both CL 0024 and MS 2053 have enhanced star formation compared to other clusters at similar redshift, and both have bimodal redshift distributions. CL 0024 is made of two colliding subclusters (Czoske et al. 2002) and has an unusually large number of luminous infrared galaxies (Coia et al. 2005). Similarly, Tran et al. (2005) conclude that MS 2053 has a significant number ($>25\%$) of infalling galaxies; these members tend to be blue and star forming. Both CL 0024 and MS 2053 are accreting a large number of new members and have high fractions of dusty star-forming galaxies. We speculate that the increase in star-forming members reflects the recent accretion of new members, i.e., galaxy infall, and that such events are more frequent at higher redshift due to the process of cluster assembly (Ellison et al. 2001; Tran et al. 2005; Loh et al. 2008). As further evidence of this, 80% of the MIPS-detected galaxies in the $z \sim 0.8$ clusters are more than 700 kpc from the cluster cores in projected distance, and thus the MIR Butcher-Oemler effect is significantly altered by considering only the inner 500 kpc of the clusters (open symbols in Fig. 2).

5. SUMMARY

We present the first comprehensive study of SST/MIPS 24μm observations for eight massive, X-ray–luminous galaxy clusters spanning a wide redshift range ($0.02 < z < 0.83$). Uniform photometry, high-resolution HST imaging, and extensive redshift catalogs enable us to measure the fraction of members with strong, dust-obscured star formation. The fraction of cluster galaxies with MIR star formation rates $\geq 5 M_\odot \text{yr}^{-1}$ increases from 3% in Coma to $\sim 13\%$ in clusters at $z = 0.83$, and this trend is evident in both luminosity-selected ($M_p \leq -19.5$) and mass-selected ($M_p \geq 4 \times 10^{10} M_\odot$) samples.

Optically based studies increasingly underestimate the total amount of star formation in cluster galaxies with redshift because many of these dusty red star-forming members are missed in color-selected samples. These tend to be late-type galaxies that are red because of dust extinction which disguises their high levels of obscured star formation ($>5 M_\odot \text{yr}^{-1}$). Defining the SF fraction to include both optically blue and red, but MIPS-detected, members doubles the fraction at $z = 0.83$ from $\sim 11\%$ to $\sim 23\%$ ($R_p < 1$ Mpc).

Finally, our study indicates that the BO effect and the increase in obscured star-forming members are linked to galaxy infall: 80% of the MIR-detected members at $z \sim 0.8$ are outside the cluster cores ($R_p > 0.7$ Mpc), and the two clusters at $z < 0.8$ that are accreting a substantial number of new members also have an enhanced fraction of galaxies with MIR SF rates $\geq 5 M_\odot \text{yr}^{-1}$.

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