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THE NATURE OF DUSTY STARBURST GALAXIES IN A RICH CLUSTER AT $z = 0.4$: THE PROGENITORS OF LENTICULARS?

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ABSTRACT

We present the results of a *Spitzer* Infrared Spectrograph survey of 24 μm selected luminous infrared galaxies (LIRGs, $L_{\rm IR} > 10^{11} L_\odot$) in the rich cluster Cl 0024+16 at $z = 0.4$. Optically, these LIRGs resemble unremarkable spiral galaxies with e(a)/e(c) spectral classifications and [O II]-derived star formation rates (SFRs) of $\lesssim 2\,M_\odot\ {\rm yr}^{-1}$, generally indistinguishable from the "quiescent" star-forming population in the cluster. Our IRS spectra show that the majority of the 24 μm detected galaxies exhibit polycyclic aromatic hydrocarbon emission with implied SFRs $\sim$ 30–60 $M_\odot\ {\rm yr}^{-1}$, with only one ($< 10\%$) in the sample displaying unambiguous evidence of an active galactic nucleus in the mid-infrared. This confirms the presence of a large population of obscured starburst galaxies in distant clusters, which comprise the bulk of the star formation occurring in these environments at $z \sim 0.5$. We suggest that, although several mechanisms could be at play, these dusty starbursts could be the signature of an important evolutionary transition converting gas-rich spiral galaxies in distant clusters into the passive, bulge-dominated lenticular galaxies that become increasingly abundant in the cores of rich clusters in the $\sim$ 4 Gyr to the present day.

Key words: galaxies: active: – galaxies: clusters: individual (Cl0024+16) – galaxies: evolution – galaxies: starburst

Online-only material: color figures

1. INTRODUCTION

Passive lenticular (S0) galaxies make up a large fraction of the galaxies in clusters in the local universe (Oemler 1974), but are conspicuously absent from equivalent environments just 5 Gyrs ago at $z \sim 0.5$ (Dressler et al. 1997; Smail et al. 1997; Couch et al. 1998; Fasano et al. 2000; Treu et al. 2003). The reverse is true of star-forming spiral galaxies (Butcher & Oemler 1978, 1984; Couch & Sharples 1987), and so it has been proposed that these are the progenitors of local S0s. Although this proposal is still a contentious issue, recent work has attempted to piece together a coherent model for the evolutionary history of star-forming galaxies being assimilated from the field into distant clusters (van Dokkum et al. 1998; Treu et al. 2003; Moran et al. 2005, 2006; Poggianti et al. 1999, 2004, 2006, 2008). These models generally invoke a modification of the star formation histories and morphologies of spiral galaxies in high-density environments in order to replicate the spectral properties of the cluster population and the respective build-up and decline of the S0 and spiral cluster populations since $z \sim 0.5$ (e.g., Smail et al. 1998; Poggianti et al. 1999; Moran et al. 2007). While there are several viable mechanisms to aid in the morphological transformation of spirals to S0s: harassment, ram-pressure stripping, merging, threshing, etc. (e.g., see Gunn & Gott 1972; Moore et al. 1998; Bekki et al. 2001), the luminosities of the galaxies and in particular, their bulges indicate the need for a period of enhanced stellar mass assembly in the spheroids of spiral galaxies in clusters to transform them into bulge-dominated S0s by the present day (Balogh et al. 1999; Poggianti et al. 1999; Kodama & Smail 2001; Gerken et al. 2004).

The simplest method of enhancing the stellar mass in the bulges of cluster spirals is to invoke a starburst episode within the central few kpc of these galaxies. However, until recently there was little clear evidence for such starburst activity in these systems (e.g., Balogh et al. 1997; Poggianti et al. 1999). It has only been with the availability of sensitive mid-infrared surveys of intermediate redshift ($z \gtrsim 0.2$–0.5) clusters that potential starburst populations have been detected (Duc et al. 2000, 2004; Fadda et al. 2000; Metcalfe et al. 2003; Biviano et al. 2004; Coia et al. 2005; Geach et al. 2006; Marcillac et al. 2007; Bai et al. 2007; Fadda et al. 2008; Oemler et al. 2008; Dressler et al. 2008). The mid-infrared luminosities of the cluster members suggest bolometric luminosities of $L_{\rm IR} > 10^{11}\ L_\odot$, characteristic of Luminous Infrared Galaxies (LIRGs).

In a panoramic 24 μm mapping survey with *Spitzer Space Telescope* (*SST*), we detected for the first time a population of LIRGs distributed to large clustocentric radius in two $z \sim 0.5$ clusters (Geach et al. 2006). These galaxies' mid-infrared emission is far higher than implied from the strength of their optical star formation rate (SFR) tracers such as Hα or [OII]. Such photometric surveys give no clue to the origin of the intense dust-obscured activity pinpointed by the mid-infrared emission, which could be powered by either star formation or an active galactic nucleus (AGN). If the mid-infrared emission arises from star formation, then the star-forming regions must be highly obscured by the carbonaceous and silicate material generated by massive stars in the final phases of stellar evolution.

Equally, however, it is also possible that these LIRGs could be powered by AGNs, especially given the evidence for enhanced AGN activity in intermediate redshift clusters (e.g., Martini et al. 2006; Eastman et al. 2007). Therefore to understand the role of the luminous infrared population in the evolutionary cycle of cluster galaxies, it is critical to quantify the relative importance of starburst and AGN emission in the mid-infrared population. If this population can be conclusively shown to represent starbursting galaxies, then they could be the long-sort candidates for the progenitors of local massive S0s, seen at a time when they are assembling the bulk of their stellar mass. Moreover, the intense star formation in these distant spirals could explain the apparent young ages (∼ 5 Gyr) of stellar populations in the bulges of S0s in the cores of local rich clusters (Kuntschner & Davies 1998; Poggianti et al. 2001; Mehlert et al. 2003; Aragón-Salamanca 2007; Bedregal et al. 2008).

In this article, we use low-resolution mid-infrared spectra obtained with the Infrared Spectrograph (IRS) on-board the *SST* to determine the origin of the mid-infrared emission in a sample of 24 μm galaxies selected from one of the two clusters, Cl 0024+16 ($z = 0.39$), studied by Geach et al. (2006). We use these data to test what fraction of these galaxies could be powered by AGNs (from the strength of the polycyclic aromatic hydrocarbon (PAH) features, relative to the warm dust continuum: Rigopoulou et al. 1999; Genzel et al. 1998)—this is critical for quantifying the true level of star formation in the 24 μm cluster population. Our second objective is to determine how the cluster LIRGs' star formation histories can be linked with the relatively "quiescent" star-forming population in the clusters. Finally, we examine the potential importance of the mid-infrared sources as a feeder population for passive lenticular galaxies found in the cores of local rich clusters. We attempt to reconcile these observations with the "fossil record" of cluster galaxy evolution: do they agree with information gleaned from detailed studies of the star formation histories of S0s in local massive clusters?

Our study focuses on 24 μm selected galaxies in Cl 0024+16. This is one of the best-studied clusters at intermediate redshifts, and is one of the original "Butcher & Oemler" clusters (Butcher & Oemler 1978, 1984), shown to have a large "blue fraction" of star-forming galaxies (e.g., Dressler et al. 1997). The cluster also appears to be in the late stages of a line-of-sight minor merger that occurred ∼ 3 Gyr ago (Czoske et al. 2002)—although it is not clear how this dynamical disturbance has affected the star formation histories of galaxies in the respective components. The large observational investment in studies of this cluster, including deep ground-based optical imaging, high-resolution *Hubble Space Telescope (HST)* imaging studies (Treu et al. 2003; Kneib et al. 2003); panoramic Hα imaging (Kodama et al. 2004); *Galaxy Evolution Explorer* (*GALEX*) UV imaging (Moran et al. 2006); mid-infrared *SST* MIPS and IRS coverage (Geach et al. 2006), as well as wide-field optical spectroscopy (e.g., Czoske et al. 2001; Moran et al. 2007), results in an exquisite data set with which to explore the properties of the star-forming population in this cluster.

Moran et al. (2006) investigated the (rest-frame) far-UV (FUV) properties of so-called "passive spirals" in Cl 0024+16 (galaxies with spiral morphologies but with no apparent ongoing star formation). Their red FUV–optical colors (compared to the general spiral population) suggests that star formation has recently been truncated in these galaxies. Moran et al. (2007) favor a scenario where gas is prevented from cooling onto the disks of these galaxies, thus preventing new star formation: "starvation." It has been argued that these galaxies are in a transitory phase between active spiral and passive lenticular galaxy, with gentle truncation of star formation on timescales of ∼ 1 Gyr allowing for residual star formation during a longer morphological transformation. Yet it is still not clear whether typical spirals' luminosities are sufficient to build up the brightest lenticulars found in local clusters (Poggianti et al. 1999; Kodama & Smail 2001). Thus, part of the motivation of this work is to understand where the LIRGs fit into this evolutionary scenario, and whether these luminous galaxies can contribute significantly to the passive, red color–magnitude sequence in local clusters.

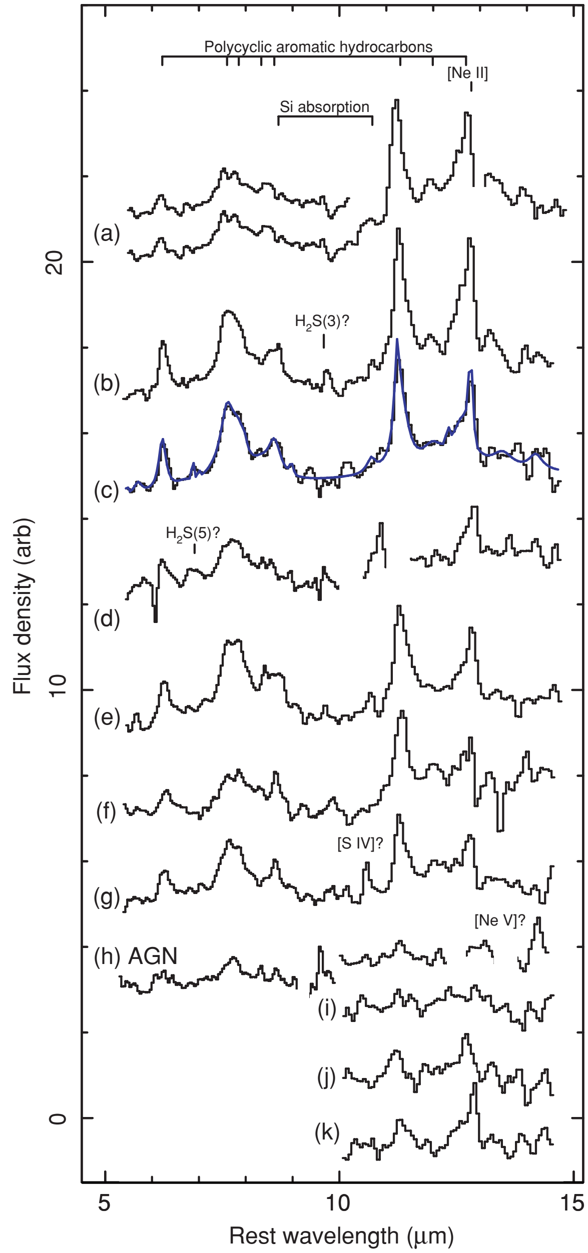

Figure 1. Mid-infrared spectra for 24 μm selected galaxies in Cl 0024+16 (offset in flux density for display purposes). We show one example of the fit resulting from the spectral decomposition from PAHFIT (spectrum c) clearly showing the good agreement with the data ($\chi^2 \sim 1$). We label the main spectral features—most galaxies exhibit strong PAH emission at 6.2–12.7 μm (note that PAH 12.7 μm is blended with [Ne II]λ12.813 μm, resulting in the sharp red wing of that line). One galaxy is undetected in either SL1 or LL2 modules and we do not show that spectrum. In addition, three galaxies have no detectable continuum in the SL1 module, and so we only show the > 10 μm (LL2) portions. These have weak PAH emission and are amongst the faintest of our 24 μm sample. One galaxy is classified as an AGN (h), with a red continuum and weak PAH emission (a bright X-ray counterpart confirms this classification). One of the IRS observations (spectrum a) shows two galaxies in close proximity, both revealing two starburst spectra in the SL1 module. We conclude that the majority of 24 μm detected galaxies in Cl 0024+16 are dusty starburst galaxies.

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

In Section 2, we describe the IRS observations and data reduction, and present the key results in Section 3. In Section 4, we interpret our observations in terms of the potential evolutionary connection to local S0s. Section 5 concludes and summarizes this work. Throughout we will assume a cosmological model with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km s^{-1} Mpc^{-1}. Unless otherwise stated, we quote magnitudes on the Vega system.

2. IRS 7–20 μm SPECTROSCOPY

The 12 galaxies studied with IRS were selected from the 24 μm MIPS survey of Cl 0024+16 which is one of the two intermediate clusters studied by Geach et al. (2006). These 12 galaxies have optical spectroscopic redshifts confirming them as members of the cluster Cl 0024+16 based on the extensive spectroscopic surveys of this cluster (Czoske et al. 2001; Moran et al. 2007). In the target selection, we imposed a 24 μm flux limit of $S_{24} > 0.6$ mJy after assuming a spectral shape of $\nu^{-1.5}$ to the underlying continuum, allowing us to estimate the expected continuum flux density at 10.9 μm (the PAH 7.7 μm feature is redshifted to this wavelength at $z \sim 0.4$).

The 24 μm flux limit, and cluster membership were the only selections we imposed, and we stress that our sample comprises 12 of the 13 galaxies with $S_{24} > 0.6$ mJy and $|\Delta v| < 4500$ km s^{-1} (with respect to the cluster redshift) detected in our MIPS survey. We note that the sample has a spread in clustocentric radius representative of the whole MIPS-detected cluster population, with $r_c \sim$ 1–5 Mpc (see Section 3 for more details).

The observations were executed in the Cycle 3 GO project # 30621 in 2006 August and 2007 August. IRS was used in fixed single staring in modes Short Low 1 (SL1; 7.4–14.5 μm) and Long Low 2 (LL2; 14–21.3 μm), with peak-up acquisition on a nearby 2MASS-selected star (HD 2292 was a suitable peak-up object for all of our targets). After peak-up and slew, the exposure time is divided into 5×60 s cycles in SL1 and 20×120 s cycles of LL2, yielding a total on-object integration time of ~ 5.5 ks. The infrared backgrounds were dominated by zodiacal light in each module, and are in the "medium" category.

We use data products generated by the *SST* IRS pipeline.[6] This processing involves dark subtraction, linearity correction, ramp correction, and flat fielding. Backgrounds were removed by subtracting two different nod positions, and the one-dimensional spectra optimally extracted using the latest available release of the SPICE software package (version 2.0.5). This took into account uncertainty and mask images, and the resulting spectra from each nod position were co-added, rejecting outliers. Note that all of our targets are treated as point sources (the width of the IRS slit is 10.″5).

3. RESULTS

3.1. Mid-Infrared Spectra

The spectra are presented in Figure 1, and measurements are summarized in Table 1. Eleven of the 12 targets are well detected in the LL2 module, with the brightest eight also showing detectable continuum in the shorter wavelength SL1 module. Only one of the galaxies (MIPS J002624.3) was not detected in either IRS module. We note that this galaxy is at the faint end of the 24 μm selected sample and in addition its optical spectrum shows a passive (k) spectral type, with no nebular emission, but a strong 4000 Å break, with $D_n(4000) = 2.3$ (Czoske et al. 2001). Thus, its lack of any mid-infrared line emission may simply reflect that fact that its mid-infrared emission originates from an AGN with a faint 5–15 μm continuum. We also note that other LIRGs with similar 24 μm flux densities ($S_{24} \sim$ 0.6–0.7 mJy) are only detected in the LL2 module (Table 1 and Figure 1).

3.2. Star Formation Versus AGN

It is immediately clear from Figure 1 that the majority of the galaxies show PAH emission and this is convincing evidence that the bulk of the 24 μm selected galaxies in Cl 0024+16 are dusty starbursts. Using the line-to-continuum starburst/AGN classification scheme of Rigopoulou et al. (1999), these galaxies would have $(l/c) \sim 2.4$, whereas AGNs have $(l/c) < 1$ due to the low contrast of PAH features above the continuum (see also Genzel et al. 1998). Half of the sample shows strong and unambiguous PAH emission at 7.7 and 11.3 μm (as well as 6.3, 8.6, and 12.8 μm). In the fainter sources, e.g., MIPS J002637.3 or MIPS J0002620.2, continuum is only detectable in the LL2 module, but 11.3 μm PAH is still visible.

Only one galaxy shows unambiguous evidence for AGN-dominated mid-infrared emission. MIPS J002636.3 (Figure 1(h)) has very weak PAH emission (low-significance 7.7 and 11.3 μm emission), a strongly red continuum, and tentative detection of the [Ne V] emission line. The ratio of line strengths [Ne V]/[Ne II] can be used as a diagnostic of starburst/AGN contribution (Sturm et al. 2002), with [Ne V]/[Ne II] generally in the range $\sim$ 0.8–2 for AGN-dominated systems, compared to strict upper limits for starburst-dominated systems of < 0.01 (Sturm et al. 2002; Verma et al. 2003). We do not detect [Ne II] at 12.8 μm in this source, suggesting [Ne V]/[Ne II] $\gtrsim 1.6$, and only very weak PAH 7.7 μm which suggests that this object is almost certainly dominated by an AGN. Most convincingly, however, inspection of archival *Chandra* X-ray imaging of the cluster reveals that this galaxy is coincident with a bright X-ray counterpart, with $L_{0.5-2\,\mathrm{keV}} = 2 \times 10^{43}$ erg s^{-1} (Soucail et al. 2000) confirming this classification. Interestingly, its optical spectrum does not show obvious evidence for nuclear activity, but instead shows poststarburst (k+a) signatures, with no [O II] emission, but EW(Hδ) = 4.8 ± 2.3 Å suggesting that an episode of star formation has ended within $\sim$ 1 Gyr (Poggianti & Wu 2000)—although we caution that the nebular emission lines might be very heavily extincted. Evidence of weak PAH emission in the mid-infrared spectrum might hint that there is some level of ongoing star formation. However, it is likely that the bulk of the mid-infrared emission is coming from the AGN: the ratio $L_X/L_{\mathrm{IR}} \sim 0.03$ measured for this galaxy is consistent with the infrared X-ray properties of local AGNs (Alexander et al. 2005).

The discovery of just a single AGN-dominated source in our sample of 12 24 μm selected cluster members indicates that the vast majority, $\gtrsim 75\%$ (including nondetections and ambiguous cases), of the bright 24 μm population in Cl0024+16 have mid-infrared emission dominated by star formation. This confirms the validity of the previously untested assumption of a dominant starburst component in this population used in the analysis of Geach et al. (2006) and all other papers analyzing mid-infrared surveys of distant clusters to date. For the remainder of this paper, we concentrate on understanding the properties of the dusty starbursts in our sample and their significance for models of cluster galaxy evolution and the total SFR in the cluster.

6 http://ssc.spitzer.caltech.edu/irs/

Table 1
Properties of MIPS Cluster Galaxies Targeted with IRS

Catalogue Name (Short Name)	(1) R.A. (h m s)	(2) Dec. (° ′ ″)	(3) z	(4) S_{24} (mJy)	(5) $F_{7.7}$ (10^{-17} W m^{-2})	(6) $F_{11.3}$ (10^{-17} W m^{-2})	(7) SFR(IR) ($M_\odot$ yr^{-1})	(8) Optical Class	Note
MIPS J002606.1+170416.4 (a)	00 26 06.1	+17 04 16.4	0.3904	1.97	5.6 ± 0.8	3.1 ± 0.2	34 ± 10	...	
MIPS J002721.0+165947.3 (b)	00 27 21.0	+16 59 47.3	0.3964	1.48	9.6 ± 0.6	4.6 ± 0.2	59 ± 16	e(a)	$H_2S(3)$?
MIPS J002621.7+171925.7 (c)	00 26 21.7	+17 19 25.7	0.3809	0.95	9.1 ± 0.6	2.9 ± 0.2	56 ± 16	e(c)	$H_2S(5)$/[Ar II]?
MIPS J002715.0+171245.6 (d)	00 27 15.0	+17 12 45.6	0.3813	0.95	5.6 ± 0.9	0.6 ± 0.3	35 ± 11	...	Weak 11.3 μm & [Ne II]?
MIPS J002652.5+171359.9 (e)	00 26 52.5	+17 13 59.9	0.3799	0.84	10.1 ± 1.3	3.9 ± 0.3	62 ± 19	e(c)	
MIPS J002609.1+171511.5 (f)	00 26 09.1	+17 15 11.5	0.3940	0.77	4.6 ± 0.9	2.9 ± 0.2	28 ± 9	e(c)	
MIPS J002703.6+171127.9 (g)	00 27 03.6	+17 11 27.9	0.3956	0.71	6.8 ± 0.8	2.3 ± 0.2	42 ± 12	e(a)	[S IV]?
MIPS J002636.3+165926.0 (h)	00 26 36.3	+16 59 26.0	0.4063	0.70	V. weak	...	...	k+a	AGN (X-ray source)
MIPS J002633.7+171221.4 (i)	00 26 33.7	+17 12 21.4	0.3958	0.68	...	V. weak	...	e(a)	LL 2 only
MIPS J002620.2+170407.4 (j)	00 26 20.2	+17 04 07.4	0.3963	0.67	...	Weak	...	e(a)	LL 2 only
MIPS J002624.3+171129.8 (k)	00 26 24.3	+17 11 29.8	0.3943	0.67	...	...	...	k	Not detected
MIPS J002637.3+170055.1 (l)	00 26 37.3	+17 00 55.1	0.3970	0.61	...	Weak	...	e(c)	LL 2 only

Notes. (1 and 2) Coordinate is centroid of 24 μm detection, J2000. (3) Redshift determined from optical spectroscopy (Czoske et al. 2001; Moran et al. 2007). (4) 16″ aperture-corrected flux density from Geach et al. (2006). Typical uncertainty is 0.04 mJy. (5 and 6) PAH 7.7 and 11.3 μm line flux estimated from the spectral decomposition code PAHFIT (Smith et al. 2007). The total line flux is the total for the PAH line blends, and models the individual aromatic emission modes as Drude profiles. (7) SFR derived from the FIR luminosity (Kennicutt 1998), estimated from the 7.7 μm line luminosity (see Section 3.1 for more details). (8) Optical classification scheme from the Morphs collaboration (Dressler et al. 1999) based on the equivalent widths of [O II] and Hδ.

3.3. *Composite Spectrum and Comparison to Optical Properties*

Since we have precise redshifts for these starburst-classified galaxies (from their optical spectra), we can co-add the rest-frame IRS spectra into a composite "star-forming" spectrum shown in Figure 2. This yields the mid-infrared spectrum of a typical galaxy with better signal-to-noise than in the individual spectra, and clearly shows strong PAH emission at 6.3, 7.7, 8.6, 11.3 with a PAH/[Ne II] blended line at 12.7 μm. For comparison, we show the equivalent composite optical spectrum for these galaxies (Moran et al. 2007; Czoske et al. 2001). It resembles a typical spiral galaxy, with signatures of dust-obscured star formation—it would be classified as e(a) in the nomenclature of the *Morphs* collaboration (Dressler et al. 1999). It has relatively weak [O II] emission, implying ongoing unextinguished star formation with rates of SFR([O II]) $\lesssim 2\ M_\odot$ yr^{-1}. The moderate Hδ absorption suggests that there has been massive star formation on a timescale of $\lesssim 1$ Gyr (Poggianti et al. 1999). Turning to the full sample of 24 μm detected members of Cl0024+16, of all the $S_{24\,\mu\mathrm{m}} > 0.2$ mJy galaxies in Cl 0024+16 with spectral classifications from Czoske et al. (2001) and Moran et al. (2007), 53 ± 12% are e(c), 29 ± 9% are e(a), 5 ± 4% are k+a (including the AGN described above) with the remainder classified as k (passive). Hence, the majority of them fall into the moderately star-forming classes, e(c)—characteristic of normal spirals or e(a)—a classification that has been argued as an optical signature of a dusty starburst (Poggianti & Wu 2000). We note that our IRS subsample (i.e., those bright in the MIPS waveband, $S_{24\,\mu\mathrm{m}} > 0.6$ mJy), has a slightly higher fraction of e(a) galaxies: 40% ± 20%. This might hint that the optically identified dusty starbursts (i.e., the e(a) class) may be biased toward the most active galaxies (see also Dressler et al. 2008), and lower (but still significant) levels of star formation are hidden in the more numerous, but less extreme, e(c)-classified MIPS cluster members.

The mid-infrared spectra of these galaxies (Figures 1 and 2) reveal that these galaxies are actually undergoing significantly more star formation than the optical nebular lines would suggest. We compare the cluster LIRGs' composite mid-infrared spectrum to a composite spectrum extracted from the nuclear regions of a sample of local starbursts (Brandl et al. 2006) and a "disk-averaged" composite spectrum constructed from a selection of SINGS galaxies (Smith et al. 2007).[7] Although there is broad agreement between the features in all the spectra (especially at $\lambda < 10\ \mu$m), our cluster LIRGs show stronger emission at longer wavelengths, $\lambda > 10\ \mu$m, than either of the two local templates—although they are more similar to the the local nuclear starburst spectrum. We have attempted to improve the match between the local templates and the cluster LIRGs by modifying the SINGS' (or local nuclear starburst) composite spectrum through the addition of a power-law continuum (mimicking a contribution from hot dust), combined with Galactic center extinction (Chiar & Tielens 2006). Although such a model allows us to better match the continuum in the cluster LIRGs' spectra at > 10 μm, it still fails to match the PAH line ratios (the 11.3/7.7 μm PAH line ratio is particularly sensitive to the gradient in the reddening curve, $A_{11.3}/A_{7.7} \sim 2$ in this model). To achieve a good match, we would have to enhance the 11.3 μm and 12.7 μm PAH features in the SINGS spectrum, however the physical motivation for such a change is uncertain and complex (related to metallicity, grain ionisation fraction, dust size distribution, etc.; see Draine & Li 2001; Calzetti et al. 2007), and so we feel it is unjustified here.

Nevertheless, we take the similarity between the nuclear starburst spectrum and our galaxy-integrated spectrum as suggestive that the cluster LIRGs are dominated by a similar (nuclear) mode of star formation. The best local analog of the cluster LIRGs from the Brandl sample is NGC3310. This UV- and IR-bright starburst has morphological signs that it has recently undergone a minor merger, and (like many starbursts) has star formation concentrated in a circumnuclear ring (Conselice et al. 2000). The mixture of bright UV and IR emission suggests that the star-forming regions of this galaxy are differentially obscured according to age (e.g., Poggianti et al. 2001)—this might explain the weak spectroscopic signature of a significant population of O stars (Leitherer et al. 2002). In the next section, we

[7] Selected such that their angular size is most comparable to the IRS slit, and therefore approximate to galaxy-integrated spectra.

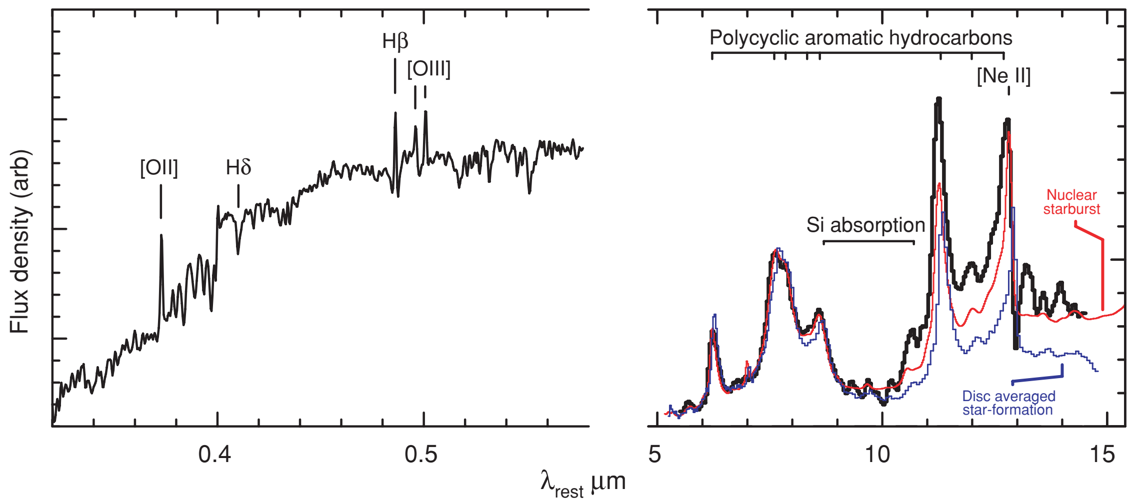

Figure 2. Composite starburst spectrum for cluster LIRGs, shifted to the rest frame. The left-hand panel shows the composite optical spectrum (normalized to unity flux density at 3727 Å). The main features of the optical spectrum is moderate [O II] emission [EW([O II])= 10.5 ± 1.0 Å] and relatively strong Hδ (and Balmer) absorption [EW(Hδ) = 4.6 ± 0.9 Å]: classified as e(a) in the nomenclature of Dressler et al. (1999), and other works. The right-hand panel shows the composite (starburst) mid-infrared spectrum (normalized to unity 7.7 μm, with the shaded region representing the 1σ uncertainty). We compare to the composite nuclear starburst spectrum of Brandl et al. (2006), and a composite "disk-averaged" spectrum of star-forming galaxies from the SINGS sample (Smith et al. 2007; see Section 3). The spectra are all very similar at $\lambda < 10$ μm, but there is much better agreement with the nuclear starburst spectrum, especially at longer wavelengths. If the spectral features (silicate absorption, continuum strength, line ratios, etc.) are connected to the properties of the star-forming interstellar medium (ISM), then we suggest that the mode of star formation in the cluster LIRGs is similar to local nuclear starbursts, as opposed to the relatively quiescent star formation seen in galactic disks. See Section 3 for more details.

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

use the PAH emission features to estimate total infrared (TIR) luminosities, and thus more reliable SFRs for cluster LIRGs.

3.4. *Star Formation Rates*

In the presence of dust, infrared tracers of star formation are more reliable than optical calibrations. In our previous photometric study (Geach et al. 2006), we estimated the total 8–1000 μm emission from cluster LIRGs by assuming a simple ratio between the observed 24 μm continuum emission and the TIR luminosity based on a library of dusty starburst spectral energy distributions (SEDs) characterized by a power-law distribution of dust mass (Dale & Helou 2002 (D&H)). This result was consistent with the local relation between 15 μm and FIR luminosity (Chary & Elbaz 2001), but using our new IRS spectra we can now improve the choice of the appropriate model SED and hence the predicted bolometric luminosities. The *Spitzer* 24 μm MIPS band traces the integrated emission at $\lambda_0 \sim 15$–$19\,\mu$m in the cluster member's rest frame. This region of the mid-infrared spectra of galaxies contains both PAH emission, continuum emission, and silicate absorption (not modeled in the D&H SEDs), and so the spectral variation inherent to star-forming galaxies (e.g., Draine et al. 2007; Smith et al. 2007) could result in significant over or underestimation of the total SFR, depending upon the precise mix of absorption and emission in the MIPS band. Alternatively, if the galaxy contains an AGN, we could erroneously overestimate the SFR—thus one of the main objectives of this work was to obtain an unambiguous, accurate SFR estimate for cluster LIRGs.

The new IRS spectra provide a more accurate picture of the nature of the mid-infrared emission, which is superior for deriving SFRs. This is not only because the emission features are more closely correlated with the intensity of the ionizing UV photons from massive stars, but also since the total mid-infrared emission can be dominated by these features (Smith et al. 2007). Our estimates of the PAH line luminosities are derived by fitting the 5–15 μm rest-frame spectra with PAHFIT,[8] the spectral decomposition code of Smith et al. (2007). This method models the PAH dust features as Drude profiles (appropriate for harmonic oscillators—the C–H bonds in PAH molecules). The derived PAH 7.7 μm and PAH 11.3 μm line fluxes are presented in Table 1.

Although the PAH features are thought to arise directly from the excitation of molecules by UV emission associated with massive star formation, the complex physics of the macro-molecules means that directly linking PAH line luminosity to SFRs remains a challenge (e.g., Wu et al. 2005). An alternative method is to use the PAH emission as a proxy for the TIR emission; there is a tight correlation between PAH line and TIR emission in galaxies spanning a wide range of redshift and luminosity (Peeters et al. 2004; Brandl et al. 2006; Schweitzer et al. 2006; Pope et al. 2008). Here we adopt the PAH 7.7 μm line to estimate the bolometric luminosity.[9] To calibrate $L_{\mathrm{PAH\,7.7}}$ to TIR (8–1000 μm) luminosities, we compare $L_{\mathrm{PAH7.7}}/L_{8-1000}$ for H II-dominated galaxies (i.e., star-forming) selected from the SINGS catalog (Smith et al. 2007). These galaxies span several orders of magnitude in both TIR and PAH luminosity with a clear linear trend between the two (Figure 3). We find

$$\log(L_{\mathrm{IR}}/L_\odot) = (1.01 \pm 0.01)\log(L_{\mathrm{PAH7.7}}/L_\odot) + (1.27 \pm 0.05). \quad (1)$$

Note that this differs in part from calibrations presented in other works (e.g., Pope et al. 2008), since here we are using the Drude profile to estimate line luminosities, whereas other studies have used alternative methods to estimate the PAH line strengths (spline fitting, Gaussian profiles, etc.) which tend to result in

8 http://turtle.as.arizona.edu/jdsmith/pahfit.php

9 We refer to the "PAH 7.7 μm" feature—in fact, this is a blend of several PAH emission lines, and the luminosities reported here are the total for the blended feature; see Smith et al. (2007) for more details on the spectral decomposition. The reader should also note that PAHFIT overestimates line fluxes by a constant factor $(1 + z)$, but our spectra were fit in their rest frame.

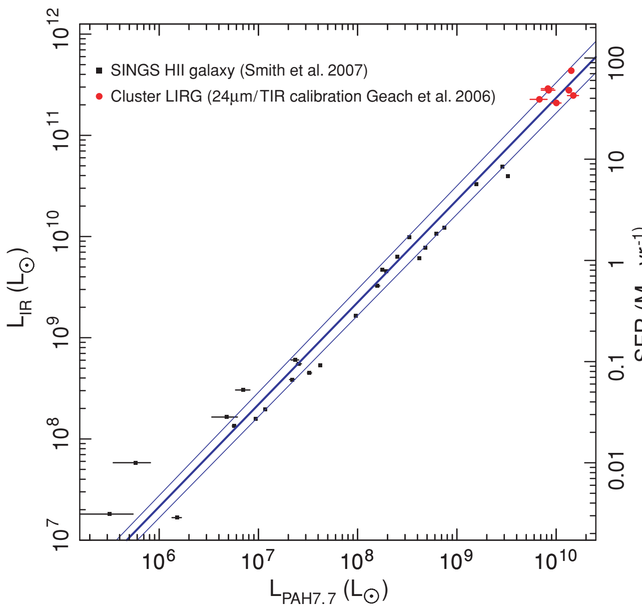

Figure 3. Calibration of TIR (8–1000 μm) luminosities from the luminosity of the 7.7 μm blended PAH feature when measured with PAHFIT (modeling PAH emission with a set of Drude profiles, and continuum as a superposition of modified black bodies). We use the catalog of H II galaxies from the SINGS survey (Smith et al. 2007) to demonstrate that there is a strong correlation between the PAH line strength and the total bolometric output that spans over several orders of magnitude in activity. We also show the positions of our LIRG sample, with $L_{\rm IR}$ derived from our previous extrapolation from 24 μm luminosities (Geach et al. 2006). We fit a linear trend to a the $L_{\rm IR} > 10^8\ L_\odot$ data, which agrees very well with both the low-luminosity, local SINGS galaxies, and our more active LIRGs at $z = 0.4$ (the SINGS sample has been corrected for aperture losses). As a guide, we show the range of fits when the luminosity distribution is bootstrap resampled, and we take this as a conservative estimate of the typical uncertainty in our calibration. Note that the right-hand axis shows the conversion from infrared luminosity to SFR assuming the relationship in Kennicutt (1998a).

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

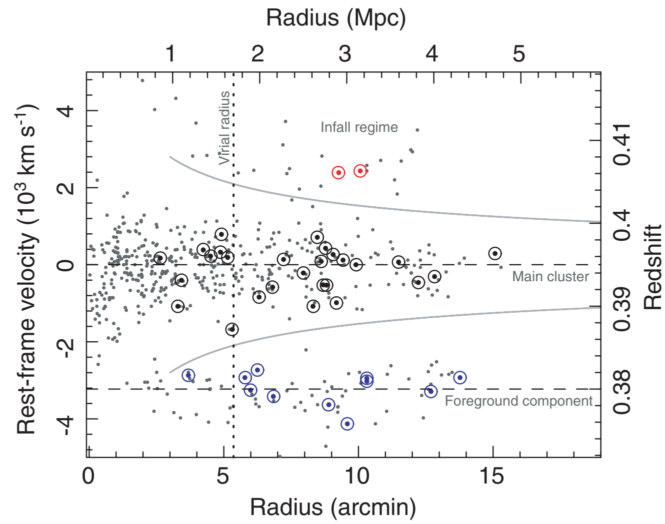

Figure 4. Velocity radial distribution of 24 μm selected ($S_{24} > 0.2$ mJy) galaxies in Cl0024+16 compared to the general cluster population (MIPS detections are circled. Note that our previous MIPS survey excluded the central $\sim$2.′5 × 2.′5 due to GTO constraints—our analysis thus concentrates on the region outside of the core). The velocity distribution shows that the cluster is actually composed of two components: the main cluster at $z = 0.395$, and a smaller "foreground" component at $\Delta v \sim -3000$ km s^{-1}. It is thought that this is the remnant of a line-of-sight group–cluster collision that occurred some $\sim$ 3 Gyr ago (Czoske et al. 2002). The curved lines show the escape velocity for the mass enclosed within a given radius (assuming $M = 8.7 \times 10^{14}\ M_\odot$ (Kneib et al. 2003) and an isothermal potential). Mid-infrared luminous galaxies are distributed out to large clustocentric radii with a velocity dispersion similar to the general spiral population—there is no convincing evidence to suggest that the luminous-obscured starbursts inhabit significantly different local environments than the majority of the star-forming population in Cl0024+16, although several LIRGs (like the lower luminosity spirals) belong to small groups.

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

systematically lower luminosities. To derive an SFR from $L_{\rm IR}$, we adopt the calibration of Kennicutt (1998a): SFR(IR) $= 4.5 \times 10^{-44} L_{\rm IR}/({\rm erg\,s^{-1}})$. The resulting SFRs are listed in Table 1. To compare to our previous estimate of the 24 μm derived SFR in these galaxies, we apply the same 24 μm/TIR calibration as in our previous work (Geach et al. 2006) and find reasonable consistency with the PAH 7.7/TIR calibration (Figure 3), with $\langle {\rm SFR(PAH\,7.7}\mu{\rm m)/SFR(24}\mu{\rm m)} \rangle = 0.77 \pm 0.29$.

Obtaining IRS spectra of a sample of LIRGs in Cl 0024+16 also provides us with a method to more accurately determine the SFRs of all 24 μm detected ($S_{24} > 0.2$ mJy) galaxies in this cluster, since we can determine the best-match local analog SED to derive $L_{\rm IR}$, instead of relying on a suite of SED types (although it is still possible that there is some variation amongst the LIRGs). While we lack spectral coverage beyond $\lambda_0 \sim 15$ μm, the 24 μm photometry provides a good estimate of the continuum level at $\lambda_0 \sim 17$ μm, thus improving any comparison where hot dust may be important. The best-matching SED in the D&H library corresponds to $\alpha = 1.6875$,[10] with an *IRAS* FIR color of $f_{60}/f_{100} \sim 0.75$.

When this SED is used in the transformation from 24 μm to TIR emission for all the 24 μm detected members of Cl0024+16, and including a conservative 25% correction for AGN contamination in the total 24 μm luminosity, we estimate a total SFR of 735 ± 150 $M_\odot$ yr^{-1} (limiting to within 2 Mpc of the core; the uncertainty is derived by bootstrap resampling the LIRG flux distribution). This compares to the original estimate of $\sim$1000 ± 210 $M_\odot$ yr^{-1} by Geach et al. (2006) and the estimate of $\sim$220 $M_\odot$ yr^{-1} derived over the same luminosity range from an Hα narrow-band imaging survey by Kodama et al. (2004). The change in our estimate of the total SFR in the cluster is driven by our new (albeit conservative) estimate of the likely AGN contamination, measured with the present IRS observations. Despite the small AGN correction, our IRS observations confirm that the dust-obscured mode of star formation dominates the most intense star-forming events in the cluster population and likely produces the bulk of the stars formed in cluster galaxies at $z \sim 0.5$.

3.5. Environment

In Figure 4, we present the velocity and radial distribution of 24 μm selected ($S_{24} > 0.2$ mJy) galaxies in Cl0024+16 compared to the general cluster population. As mentioned in Section 1, Cl0024+16 is a line-of-sight merger, visible clearly in Figure 4 by the distinct foreground component of galaxies, blueshifted by $\sim$3000 km s^{-1} with respect to the main cluster at $z = 0.395$ (Czoske et al. 2002). Note that the large fraction (similar to the main cluster) of 24 μm detected galaxies in the foreground component is interesting: if these galaxies were members of this cluster prior to the collision, then they must have been subjected to a high-speed pass through the intracluster medium (ICM) of the main cluster. As evidenced by their high

[10] The D&H library of SEDs are characterized by α, the exponent in the power-law distribution of the mass of dust over the intensity of the dust-heating radiation field: ${\rm d}M_{\rm d}(U) \propto U^{-\alpha}{\rm d}U$. See Dale & Helou (2002) for more details.

SFRs, they did not lose their internal gas reservoirs during this episode, implying that they have not been ram-pressure stripped. Alternatively, these starburst galaxies may have been accreted onto the foreground component some time after the collision.

Focusing our attention on the main cluster, the 24 μm detected members have similar velocity and radial distribution to nondetected spirals, with an average clustocentric radii of $r_c = 2.7 \pm 1.0$ Mpc, $\sigma = 857 \pm 426$ km s^{-1}, and $r_c = 2.4 \pm 0.9$ Mpc, $\sigma = 969 \pm 214$ km s^{-1} measured for the two populations respectively.[11] For comparison, the E/S0 galaxies have a slightly lower velocity dispersion, $\sigma = 776 \pm 77$ km s^{-1} (but a similar radial distribution if one excludes the central region not covered by the Geach et al. 2006 MIPS sample, $r_c = 2.4 \pm 1.0$ Mpc). This kinematic difference can be attributed to the fact that the MIPS-detected population and the less active spiral galaxies predominantly stem from accretion (infall) from the field and are not yet fully virialized.

We find no evidence that LIRGs have significantly different local environments to the general cluster population, but (like the general spiral population) several LIRGs appear to be members of small groups. One of these groups contains two 24 μm detected members, and is at a large relative velocity compared to the main component (~ 2500 km s^{-1}). Incidentally, one of these galaxies is the AGN in our IRS sample (MIPS J002636.3; Table 1, row h; Figure 1(h)). This is probably part of a small-bound group of galaxies falling into the cluster. Several more 24 μm detected members are part of a large substructure to the northwest of the main cluster core. It is possible that some of the triggering of starburst (and AGN) activity in Cl0024+16 occurs through interactions within these small-bound groups. Evidence of this behavior can be seen in Figure 1(a): two cluster members were detected in the IRS SL1 mode (they were at a close separation and both fell on the slit); both are bright enough in the mid-infrared that we can see that they have very similar, dusty starburst spectra.

If we parameterize the galaxies' local environment with the Dressler–Shectman (DS) statistic (Dressler & Shectman 1988), we find no statistical difference between the starbursting LIRGs and "quiescent" spirals—which display similar local environments. However, as noted by Moran et al. (2007) and described above, the overall level of substructure in Cl0024+16 could have significant implications for the evolution of the star-forming population, with galaxies much more likely to have been subject to "preprocessing" in small-bound groups prior to cluster assimilation. We interpret the similarity in environmental properties between 24 μm selected and normal spirals in Cl0024+16 as an indication that the LIRGs are simply the bright tail of the star-forming population in this cluster, whose enhanced activity does not reflect a unique environment, but rather points to these galaxies being particularly gas-rich.

3.6. *Morphologies*

An important aspect of the proposed evolutionary link between cluster spirals and S0s is the necessity for a morphological transformation. Luckily, a fraction of the LIRG members of Cl0024+16 fall within the sparse *HST* WFPC2 mosaic of the cluster (Treu et al. 2003), and therefore can be classified morphologically. From our IRS sample, we have WFPC2 imaging of three galaxies and we supplement this small sample in Figure 5 with the remainder of 24 μm selected cluster members with $S_{24} > 0.2$ mJy that are covered by the *HST* survey to demonstrate the range of morphologies for the population. We find that 80% of the LIRGs with classifications are designated as early-type spirals (Sab or earlier), although several galaxies exhibit obvious spiral arm structure and most have prominent disk components. Of the full sample, eight galaxies have bright bulges and/or nuclear point sources, and five have evidence for recent or ongoing interactions (we cannot rule out advanced mergers in some cases); while several galaxies exhibit slightly disturbed morphologies. This might be evidence of recent processing in the cluster environment or in small groups (e.g., harassment, high-speed encounters in the cluster potential, etc.). As described above, LIRGs appear not to have significantly different local environments to the general spiral population, however evidence of disturbed morphologies hints that local dynamical disturbances have a role in triggering star formation over all luminosities (and in the case of LIRGs, potentially help in completing the spiral-to-S0 morphological transformation by subsequently erasing any remaining spiral structure).

4. DISCUSSION

The results presented above highlight the fact that our understanding of the evolutionary history of cluster galaxies is still incomplete. The vigorous star formation which our IRS spectra have uncovered in the cluster LIRG population means that these galaxies are potentially good candidates to evolve into the lenticular galaxies that become more abundant in the cores of rich clusters at $z \lesssim 0.5$. In the following discussion, we examine this scenario, concentrating mainly on the star formation properties and histories of cluster galaxies in Cl0024+16.

4.1. *The Star Formation Histories of Cluster LIRGs*

It is clear from studies of generally passive galaxy populations in local clusters that the eventual fate of gas-rich spiral galaxies entering clusters at high redshift must be the cessation of their star formation. It is not clear precisely what mechanisms control this evolution: there are a wide range of processes occurring in cluster environments that could potentially affect the star formation histories of galaxies traversing the cluster potential (e.g., Gunn & Gott 1972; Cowie & Songaila 1977; Dressler & Gunn 1983; Bekki 1998; Moore et al. 1998, 1999).

As we showed in Section 3.5, the mid-infrared starburst galaxies share similar environmental conditions to the less active spirals. It is therefore reasonable to assume that both populations are subject to similar environmental processing. This suggests that the enhanced SFRs seen in the LIRGs owes more to the galaxies' individual properties than their environment. Although perhaps not true of all clusters, in terms of the survival of star formation, Cl0024+16 appears to exert a weak influence on infalling spiral galaxies (Moran et al. 2007).

In fact, ram pressure stripping can largely be ruled out as an effective truncation mechanism for the starburst population in Cl0024+16: stripping is only effective within $\sim$1 Mpc of the core, and the majority of the mid-infrared sources are outside this region (Figure 4). The typical timescale for galaxies to reach the core region is $\sim$1–2 Gyrs, although the actual stripping timescale is comparatively short (a few tens of Myr) once the galaxies reach the highest density regions (see the discussion in Treu et al.

[11] We only consider cluster members in the main cluster component and with radii >0.85 Mpc, matching the region covered by our previous MIPS survey. Velocity dispersions are calculated from the biweight scale of the distribution (Beers et al. 1990) with an uncertainty derived from bootstrap resampling the velocity distribution.

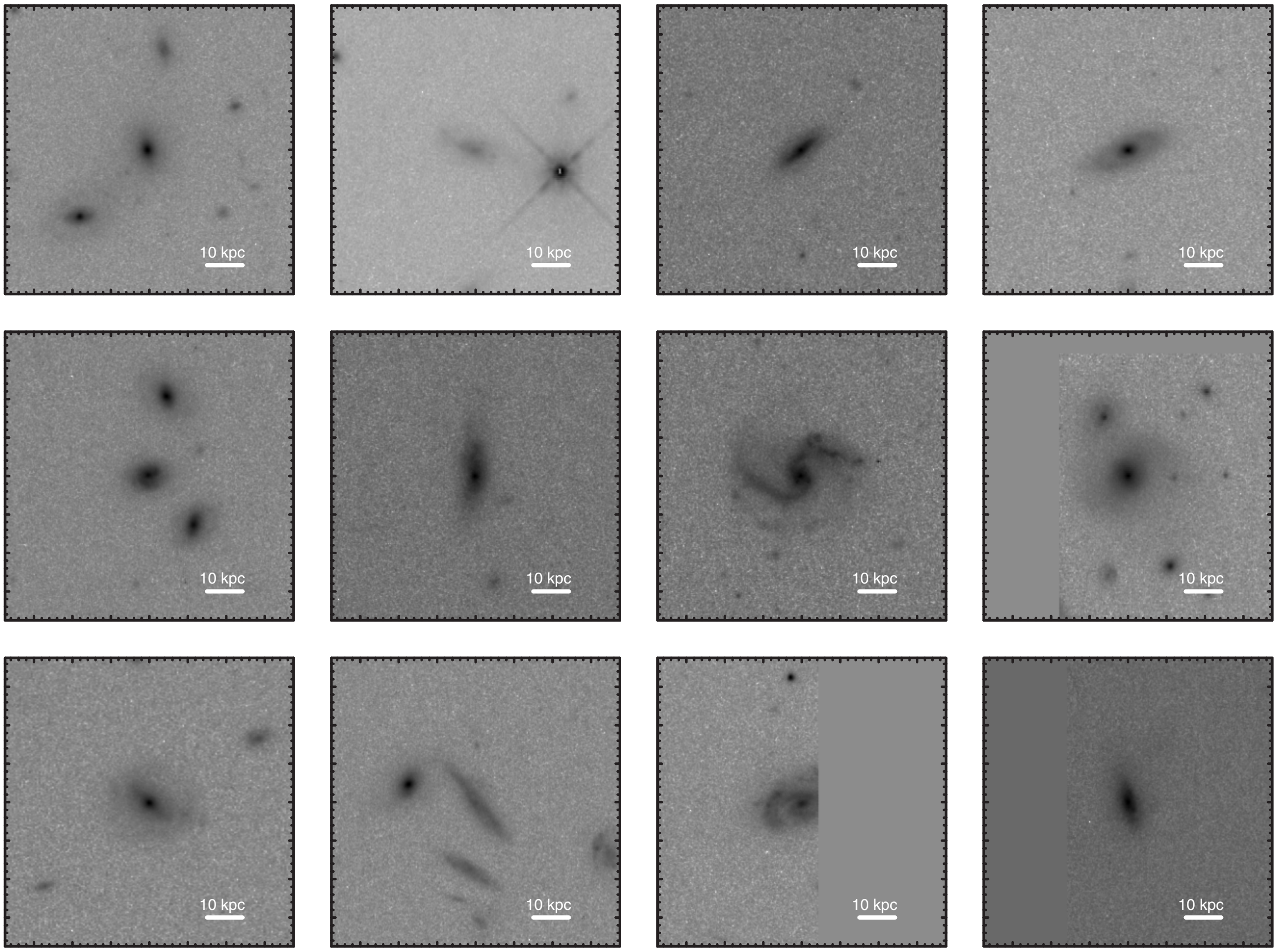

Figure 5. *Hubble Space Telescope* WFPC2 (F814W, rest-frame V-band) images of 12 $S_{24} > 0.2$ mJy members of Cl0024+16. We see a range of morphologies, although many galaxies appear to be relatively early-type spirals. All images are $15'' \times 15''$ ($\sim 80 \times 80$ kpc), and ordered from left to right, top to bottom in increasing infrared luminosity. The images have been smoothed with a Gaussian filter (kernel FWHM 250 pc) and are logarithmically scaled.

2003 for more details). However, the lifetime of the starburst events in these galaxies is likely to be of the order of 100 Myrs (see Section 4.3), thus, by the time LIRGs reach the cluster core, their bursts will be long since over, and so (for Cl0024+16 at least) ram pressure stripping is unlikely to play a dominant role in modification of LIRGs' star formation histories. A caveat, as noted by Moran et al. (2007), is that the presence of significant substructure in the cluster could give rise to shocks in the ICM that might exert significant ram pressure at comparatively large clustocentric radius—potentially responsible for the triggering of star formation in infalling groups. If we assume that it is the core regions where truncation of star formation takes place, how will this affect the LIRGs? Most likely, once the LIRGs sink to the bottom of the potential well, any residual star formation they do have will be finally extinguished, but their major epoch of star formation will have already occurred.

Moran et al. (2007) propose that spiral galaxies in Cl 0024+16 experience a gentle "starvation" of their gas reservoirs as they encroach on the potential well (i.e., residual star formation exhausts gas reservoirs, with no replenishment from cooling onto the disk). This model has been used to support the scenario where spirals are gradually transforming into passive lenticulars (or dwarf spheroidals), but it is not clear that typical starved spirals can account for the formation of the most luminous lenticulars found in local clusters. Starvation is evidently irrelevant for LIRGs, since their gas will probably be converted to stars in a short period (few 100 Myrs) compared to the 1 Gyr truncation timescale of normal spirals. A natural explanation for the existence of LIRGs in Cl0024+16 is that we are observing starbursts that originated as the most gas-rich spirals in the field: these galaxies can achieve high-bulge luminosities at the present day without relying on replenishment of their gas reservoirs from further cooling.

If the starbursts in Cl0024+16 simply exhaust their gas reservoirs unmolested, then it is straightforward to estimate their luminosity evolution and thus compare to the properties of local cluster populations. The typical rest-frame H-band luminosity of the Cl 0024+16 LIRGs is $M_H = -24.5 \pm 0.6$ mag. Assuming complete cessation of star formation after the burst, and passive evolution until $z = 0$, we estimate a total (H-band) fading of $\Delta M_H \sim 2$–2.4 mag (the range reflects the difference between star formation histories where (1) all the stellar mass is formed in the burst, and (2) the luminosity includes a preexisting older stellar population formed continuously since $z = 5$).[12] Thus, the LIRGs descendants will have typical luminosities of $-21.5 \lesssim M_H \lesssim -23.1$ mag. This luminosity evolution appears to be sufficient to place their descendants at the bright end of the S0 luminosity function in local clusters; for example,

[12] We base these estimates on the application of the simple stellar population models of Bruzual & Charlot (2003), assuming a constant solar metallicity, and Chabrier initial mass function.

the median H-band luminosity of morphologically classified S0s in Coma is $M_H = -22.7$ mag (J. R. Lucey 2008, private communication). This is a conservative estimate, because it is feasible that some residual "quiescent mode" star formation could endure in these galaxies over the ∼4 Gyr to the present day. In contrast, the "starved" descendants of typical spirals in Cl0024+16 are not luminous enough to populate the bright end of the local S0 luminosity function, and generally have a final $M_H > -22.7$ mag (see Smail et al. 1998). We therefore suggest that the "dusty starburst phase" identified by our joint MIPS/IRS study is a key evolutionary step required to boost the luminosity of infall spirals if their progeny are to become the most massive S0s found in local clusters (Poggianti et al. 2001; Kodama & Smail 2001).

4.2. Bulge Formation: Circumnuclear Starburst?

While there may be sufficient star formation in cluster LIRGs to match the luminosities of local S0s, where is this activity occurring within the galaxies? A key requirement in the conversion of a spiral to a lenticular galaxy is the enhancement of stellar luminosity in the galactic bulge compared to the disk. A critical signature of bulge growth would be the observation of a circumnuclear starburst, where the stellar mass in the bulge can be rapidly enhanced without the need for dramatic migration of the stellar populations. Unfortunately, our current mid-infrared observations do not have the spatial resolution to confirm this mode of star formation—nevertheless, we argue that a circumnuclear starburst is a natural scenario for these galaxies.

Our evidence is largely circumstantial. As discussed in Section 3, the cluster LIRGs' galaxy-integrated spectra closely resemble that of the spectra extracted from the nuclear regions of local starbursts compared to the disk-integrated spectra of typical local star-forming galaxies (see Figure 2). Given that mid-infrared spectral properties can largely be driven by the conditions of the ISM environment, we take this similarity as a compelling hint that the LIRGs' mode of star formation occurs in a circumnuclear environment. Furthermore, the overall rate of star formation (as measured from the PAH spectral features) is hard to reconcile with an extended disk. In the local universe, starbursts tend to be centrally concentrated, given the elevated gas densities found in the nuclear regions compared to the extended disk (Kennicutt 1998a). If star formation were distributed over the disks of these galaxies (and assuming the scaling between SFR surface density and gas surface density holds), then the average gas surface densities required would be nearly an order of magnitude larger than that seen in typical star-forming disks (Kennicutt 1998b). In contrast, the gas densities found in typical compact starburst disks is much more amenable for the observed levels of star formation.

One other piece of evidence that suggests that the LIRGs have enhanced star formation in their bulges compared with their disks comes from their morphological properties (Section 3.6): ∼80% of 24 μm detected cluster members that are covered by the sparse *HST* WFPC2 mosaic are classified as early-type spirals (Sab) or earlier type (Figure 5). This could imply two things: (1) a large amount of the morphological transformation from spiral to lenticular is already complete, and all that remains is an overall boosting of luminosity, and/or (2) the bulge luminosities of these galaxies is overwhelming the disks because the current starburst is occurring in the bulge region (e.g., Bendo et al. 2002a, 2002b).

Finally, the cluster environment itself could support triggering of nuclear star formation: at large clustocentric radii, although ram pressure *stripping* is largely ineffective, the intergalactic medium (IGM)/ISM interaction can still influence star formation histories (Tonnesen et al. 2007). For example, compression of molecular clouds in the disks of infalling spirals could serve to funnel material toward the core (Kronberger et al. 2008, also see Byrd & Valtonen 1990 and Natarajan et al. 2002, 2008). We note, however, that this massaging effect could also could trigger star formation throughout the galaxy disk (Dressler & Gunn 1983; Bekki & Couch 2003). Closer to the cluster core, where stripping actually takes place, one would also expect to observe circumnuclear starbursts—this is the final (or at least hardest) region of the galaxy to be stripped of gas, and so any residual star formation is likely to occur there (but see Quilis et al. 2000).

4.3. Comparison to the Fossil Record

One experiment that would lend support for the idea that distant starbursts are feeding the population of present-day lenticulars via enhanced bulge growth would be signatures of ∼ 4 Gyr old stellar populations in the bulges of *local* cluster S0s. Spectroscopic studies of the core regions of early-type galaxies in local rich clusters have shown that a large fraction of S0s have relatively young stellar populations consistent with star formation within the past 5 Gyrs, with less luminous S0s showing younger bulge ages (Poggianti et al. 2001; Mehlert et al. 2003; Bedregal et al. 2008; Kuntschner & Davies 1998). The observed luminosity offset of local S0s from the spiral Tully–Fisher relationship is also consistent with the fading scenario described in Section 4.1 (e.g., Aragón-Salamanca 2007; M. A. Norris 2008, private communication).

In order to explain the apparent luminosity-dependent distribution of ages measured for the bulges of local S0s, either the bright end of the S0 luminosity function is made mainly up from galaxies that formed in monolithic collapse or wet mergers at high redshift $z \gtrsim 0.5$, or the most intense star formation episodes responsible for the formation of massive S0s today are increasingly common at higher redshift. This might be a reflection of the apparent strong evolution in the number density of (field) LIRGs since $z \sim 1$ (Cowie et al. 2004) compared to that of "normal" star-forming galaxies (Lilly et al. 1995). Indeed, we already have hints that this behavior is seen in cluster environments when one considers the *total* SFRs of massive clusters of galaxies since $z \sim 1$ (e.g., Geach et al. 2006). Of course, we should also consider alternative mechanisms giving rise to the local S0 populations. For example, dry merging between evolved stellar systems could also be responsible for the formation of the massive end of the S0 population (e.g., van Dokkum 2005). This leads us to the final point to address: are there sufficient numbers of these distant galaxies to explain the local abundance of passive lenticular galaxies in local clusters?

Assuming a simple evolutionary model where the LIRGs transform into S0s, one can estimate the required abundance of these galaxies in order to match the local populations (e.g., Smith et al. 2005). We apply the same model as Moran et al. (2006) for passive (starved) spirals in Cl0024+16,

$$\left(\frac{N_{\rm S0}}{N_{\rm E}}\right)_{z=0} = \left(\frac{N_{\rm S0}}{N_{\rm E}}\right)_{z=0.4} + \frac{\Delta t}{\tau}\left(\frac{N_{\rm LIRG}}{N_{\rm E}}\right)_{z=0.4}. \qquad (2)$$

Here $\Delta t = 4$ Gyr (the intervening time since $z = 0.4$) and $\tau = 100$–200 Myr, a conservative range of expected lifetimes for the starbursts. We take the Cl0024+16 S0:E abundance from Dressler et al. (1997), and apply this to the most recent spectroscopic catalog of cluster members (Moran et al. 2007) to estimate $N_{\rm E}$ in the cluster. Limiting our estimates to the fraction of $S_{24} > 0.6$ mJy (or $\log(L_{\rm IR}/L_{\odot}) \gtrsim 11.2$), LIRGs bound to the main cluster ($|\Delta v| < 2000$ km s^{-1}; see Figure 4), we find $N_{\rm LIRG}/N_{\rm E} \sim 0.04$, resulting in a local S0:E ratio of 1.5–2.3 (the range is connected to the span of LIRG lifetimes in the model). This is consistent with the observed local S0:E fraction in massive clusters: $N_{\rm S0}/N_{\rm E} = 1.7 \pm 0.6$ (Dressler et al. 1997) and implies that the observed abundances of LIRGs in $z \sim 0.5$ clusters can account for the demographics of S0s in local massive clusters.

5. CONCLUSIONS AND FINAL REMARKS

Our previous work uncovered a large population of luminous mid-infrared sources in the rich cluster Cl0024+16. This work investigated a subsample of those galaxies in greater detail, using new *Spitzer* IRS spectroscopy, specifically their mid-infrared and optical properties. Our main results can be summarized as follows.

1. The LIRGs' mid-infrared spectra confirm that the majority of the 24 μm selected galaxies in Cl0024+16 have mid-infrared emission powered by star formation. At $S_{24} > 0.6$ mJy, we derive SFRs from the 7.7 μm PAH feature of ~ 30–$60\ M_{\odot}$ yr^{-1}. Only 1/12 of our 24 μm selected sample shows unambiguous evidence of an AGN. Our PAH-derived SFRs agree well with our previously estimated SFRs from the 24 μm luminosity. In contrast to the infrared-derived SFRs, the typical optical ([O II]) derived SFRs for the same population are modest, with SFR([O II])$\lesssim 2\ M_{\odot}$ yr^{-1}. Indeed, from an optical standpoint, the LIRGs' spectra resemble spiral galaxies and are mainly classified as the potentially dusty e(a) or unremarkable e(c) galaxies in the nomenclature of Dressler et al. (1999) and subsequent works.
2. The most natural fate of LIRGs in $z \sim 0.5$ clusters is evolution into lenticular galaxies by the present day. Our arguments are supported by simple evolutionary models that show the expected luminosity evolution of the LIRGs after the cessation of star formation can match the bright end of the local cluster S0 luminosity function. At their current rates, the LIRGs in Cl0024+16 could build up a $10^{10}\ M_{\odot}$ stellar bulge in $\sim$200 Myr. We propose that the mode of starburst in the LIRGs is—like many local starbursts—circumnuclear, although this has to be confirmed with higher resolution observations beyond the scope of the current work. Such circumnuclear starbursts at $z \sim 0.5$ would favor the required bulge-to-disk evolution of a spiral–lenticular transformation, and would naturally explain the presence of ~ 4 Gyr old stellar populations observed in the bulges of some local S0s.

Spiral galaxies falling into clusters at high redshift cannot escape from the deep potential well: their descendants must exist in the cores of clusters at the present day. For three decades, the mystery of the coeval reversal in fractions of spiral/S0s in rich clusters over the past 4 Gyrs has not been satisfactorily explained. However, the mid-infrared reveals the true situation: a fraction of these galaxies are actually undergoing vigorous star formation. We argue that these galaxies will evolve into S0s by the present day—they could be the missing transition galaxies that bridge the evolutionary gap between the distant, active population of distant clusters and the passive "red and dead" lenticulars found in the local universe.

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REFERENCES

Alexander, D. M., Bauer, F. E., Chapman, S. C., Smail, I., Blain, A. W., Brandt, W. N., & Ivison, R. J. 2005, ApJ, 632, 736
Aragón-Salamanca, A. 2007, IAU Symp. 235, Galaxy Evolution Across the Hubble Time, ed. F. Combes & J. Palous (Cambridge: Cambridge Univ. Press), 8
Bai, L., et al. 2007, ApJ, 664, 181
Balogh, M. L., Morris, S. L., Yee, H. K. C., Carlberg, R. G., & Ellingson, E. 1997, ApJ, 488, L75
Balogh, M. L., Morris, S. L., Yee, H. K. C., Carlberg, R. G., & Ellingson, E. 1999, ApJ, 527, 54
Bedgregal, A. G., Aragón-Salamanca, A., Merrifield, M. R., & Cardiel, N. 2008, MNRAS, 387, 660
Beers, T. C., Flynn, K., & Gebhardt, K. 1990, AJ, 100, 32
Bekki, K. 1998, ApJ, 502, 133
Bekki, K., & Couch, W. J. 2003, ApJ, 596, L13
Bekki, K., Couch, W. J., & Drinkwater, M. J. 2001, ApJ, 552, L105
Bendo, G. J., et al. 2002a, AJ, 124, 1380
Bendo, G. J., et al. 2002b, AJ, 123, 3067
Biviano, A., et al. 2004, A&A, 425, 33
Brandl, B. R., et al. 2006, ApJ, 653, 1129
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000
Butcher, H., & Oemler, A., Jr. 1978, ApJ, 226, 559
Butcher, H., & Oemler, A., Jr. 1984, ApJ, 285, 426
Byrd, G., & Valtonen, M. 1990, ApJ, 350, 89
Calzetti, D., et al. 2007, ApJ, 666, 870
Chary, R., & Elbaz, D. 2001, ApJ, 556, 562
Chiar, J. E., & Tielens, A. G. G. M. 2006, ApJ, 637, 774
Coia, D., et al. 2005, A&A, 430, 59
Conselice, C. J., Gallagher, J. S., Calzetti, D., Homeier, N., & Kinney, A. 2000, AJ, 119, 79
Couch, W. J., Barger, A. J., Smail, I., Ellis, R. S., & Sharples, R. M. 1998, ApJ, 497, 188
Couch, W. J., & Sharples, R. 1987, MNRAS, 229, 423
Cowie, L. L., Barger, A. J., Fomalont, E. B., & Capak, P. 2004, ApJ, 603, L69
Cowie, L. L., & Songaila, A. 1977, Nature, 266, 501
Czoske, O., Kneib, J.-P., Soucail, G., Bridges, T. J., Mellier, Y., & Cuillandre, J.-C. 2001, A&A, 372, 391
Czoske, O., Moore, B., Kneib, J.-P., & Soucail, G. 2002, A&A, 386, 31
Dale, D. A., & Helou, G. 2002, ApJ, 576, 159
Draine, B. T., & Li, A. 2001, ApJ, 551, 807
Draine, B. T., et al. 2007, ApJ, 663, 866
Dressler, A., & Gunn, J. E. 1983, ApJ, 270, 7
Dressler, A., & Schectman, S. A. 1988, ApJ, 95, 985
Dressler, A., Smail, I., Poggianti, B. M., Butcher, H., Couch, W. J., Ellis, R. S., & Oemler, A. Jr. 1999, ApJS, 122, 51
Dressler, A., et al. 1997, ApJ, 490, 577
Dressler, A., et al. 2008, arXiv:astro-ph/0806.2343

Duc, P.-A., Brinks, E., Springel, V., Pichardo, B., Weilbacher, P., & Mirabel, I. F. 2000, AJ, 120, 1238
Duc, et al. 2004, in IAU Colloq. 195, Outskirts of Galaxy Clusters: Intense Life in the Suburbs, Luminous Infrared Starbursts in a Cluster of Galaxies, ed. A. Diaferio (Cambridge: Cambridge Univ. Press), 347
Eastman, J., Martini, P., Sivakoff, G., Kelson, D. D., Mulchaey, J. S., & Tran, K.-V. 2007, ApJ, 664, L9
Fadda, D., Biviano, A., Marleau, F. R., Storrie-Lombardi, L. J., & Durret, F. 2008, ApJ, 672, L9
Fadda, D., Elbaz, D., Duc, P.-A., Flores, H., Franceschini, A., Cesarsky, C. J., & Moorwood, A. F. M. 2000, A&A 361, 827
Fasano, G., Poggianti, B. M., Couch, W. J., Bettoni, D., Kjærgaard, P., & Moles, M. 2000, ApJ, 542, 673
Geach, J. E., et al. 2006, ApJ, 649, 661
Genzel, R., et al. 1998, ApJ, 498, 579
Gerken, B., Ziegler, B., Balogh, M., Gilbank, D., Fritz, A., & Jager, K. 2004, A&A, 421, 59
Gunn, J. E., & Gott, J. R., III. 1972, ApJ, 176, 1
Kennicutt, R. C. 1998a, ARA&A, 36, 189
Kennicutt, R. C. 1998b, ApJ, 498, 541
Kneib, J.-P., et al. 2003, ApJ, 598, 804
Kodama, T., Balogh, M. L., Smail, I., Bower, R. G., & Nakata, F. 2004, MNRAS, 354, 1103
Kodama, T., & Smail, I. 2001, MNRAS, 326, 637
Kronberger, T., Kapferer, W., Ferrari, C., Unterguggenberger, S., & Schindler, S. 2008, A&A, 481, 337
Kuntschner, H., & Davies, R. L. 1998, MNRAS, 295, L29
Leitherer, C., Calzetti, D., & Martins, L. P. 2002, ApJ, 574, L114
Lilly, S. J., Tresse, L., Hammer, F., Crampton, D., & Le Fevre, O. 1995, ApJ, 455, 108
Marcillac, D., Rigby, J. R., Rieke, G. H., & Kelly, D. M. 2007, ApJ, 654, 825
Martini, P., Kelson, D. D., Kim, E., Mulchaey, J. S., & Athey, A. A. 2006, ApJ, 644, 116
Mehlert, D., Thomas, D., Saglia, R. P., Bender, R., & Wegner, G. 2003, A&A, 407, 423
Metcalfe, L., et al. 2003, A&A, 407, 791
Moore, B., Lake, G., & Katz, N. 1998, ApJ, 495, 139
Moore, B., et al. 1999, MNRAS, 304, 465
Moran, S. M., Ellis, R. S., Treu, T., Smail, I., Dressler, A., Coil, A. L., & Smith, G. P. 2005, ApJ, 634, 977
Moran, S. M., Ellis, R. S., Treu, T., Salim, S., Rich, R. M., Smith, G. P., & Kneib, J.-P. 2006, ApJ, 641, L97
Moran, S. M., et al. 2007, ApJ, 671, 1503
Natarajan, P., Kneib, J.-P., & Smail, I. 2002, ApJ, 580, L11
Natarajan, P., Kneib, J.-P., Smail, I., Treu, T., Ellis, R. S., Moran, S. M., Limousin, M., & Czoske, O. 2008, ApJ, submitted
Oemler, A. J. 1974, ApJ, 194, 1
Oemler, A., Jr., Dressler, A., Kelson, D., Rigby, J., Poggianti, B. M., Fritz, J., Morrison, G., & Smail, I. 2008, arXiv:0812.4405
Peeters, E., Spoon, H. W. W., & Tielens, A. G. G. M. 2004, ApJ, 613, 986
Poggianti, B. M., Bressan, A., & Franceschini, A. 2001, ApJ, 550, 195
Poggianti, B. M., Bridges, T. J., Komiyama, Y., Yagi, M., Carter, D., Mobasher, B., Okamura, S., & Kashikawa, N. 2004, ApJ, 601, 197
Poggianti, B. M., Smail, I., Dressler, A., Couch, W. J., Barger, A. J., Butcher, H., Ellis, R. S., & Oemler, A. J. 1999, ApJ, 518, 576
Poggianti, B. M., & Wu, H. 2000, ApJ, 529, 157
Poggianti, B. M., et al. 2006, ApJ, 642, 188
Poggianti, B. M., et al. 2008, ApJ, 684, 888
Pope, A., et al. 2008, ApJ, 675, 1171
Quilis, V., Moore, B., & Bower, R. 2000, Science, 228, 1617
Rigopoulou, D., Spoon, H. W. W., Genzel, R., Lutz, D., Moorwood, A. F. M., & Tran, Q. D. 1999, AJ, 118, 2625
Schweitzer, M., et al. 2006, ApJ, 649, 79
Soucail, G., Ota, N., Böhringer, H., Czoske, O., Hattori, M., & Mellier, Y. 2000, A&A, 355, 433
Smail, I., Dressler, A., Couch, W. J., Ellis, R. S., Oemler, A. J., Butcher, H., & Sharples, R. M. 1997, ApJS, 110, 213
Smail, I., Edge, A. C., Richard, S., & Blandford, R.D. 1998, MNRAS, 293, 124
Smith, G. P., et al. 2005, ApJ, 620, 78
Smith, J. D., et al. 2007, ApJ, 656, 770
Sturm, E., Lutz, D., Verma, A., Netzer, H., Sternberg, A., Moorwood, A. F. F., Oliva, E., & Genzel, R. 2002, Bull. Am. Astron. Soc., 34, 1180
Tonnesen, S., Bryan, G. L., & van Gorkom, J. H. 2007, ApJ, 671, 1434
Treu, T., Ellis, R. S., Kneib, J.-P., Dressler, A., Smail, I., Czoske, O., Oemler, A., & Natarajan, P. 2003, ApJ, 591, 53
van Dokkum, P. G. 2005, AJ, 130, 2647
van Dokkum, P. G., Franx, M., Kelson, D. J., Illingworth, G. D., Fisher, D., & Fabricant, D. 1998, ApJ, 500, 714
Verma, A., Lutz, D., Sturm, E., Sternberg, A., Genzel, R., & Vacca, W. 2003, A&A, 403, 829
Wu, H., et al. 2005, ApJ, 636, L79