THE NATURE OF STAR FORMATION AT 24 μm IN THE GROUP ENVIRONMENT AT 0.3 ≲ z ≲ 0.55

K. D. Tyler¹, G. H. Rieke¹, D. J. Wilman², S. L. McGee³,⁴, R. G. Bower⁴, L. Bai⁵, J. S. Mulchaey⁵, L. C. Parker⁶, Y. Shi⁵, and D. Pierini²

¹ Steward Observatory, University of Arizona, 933 N. Cherry Ave., Tucson, AZ 85721, USA
² Max-Planck-Institut für extraterrestrische Physik, Giessenbachstraße, D-85748 Garching, Germany
³ Department of Physics and Astronomy, University of Waterloo, Waterloo, Ontario, N2L 3G1, Canada
⁴ Institute for Computational Cosmology, Department of Physics, Durham University, South Road, Durham DH1 3LE, UK
⁵ Observatories of the Carnegie Institution, 813 Santa Barbara Street, Pasadena, CA, USA
⁶ Department of Physics and Astronomy, McMaster University, 1280 Main Street West, Hamilton, Ontario, L8S 4M1, Canada

Received 2010 October 7; accepted 2011 June 7; published 2011 August 11

ABSTRACT

Galaxy star formation rates (SFRs) are sensitive to the local environment; for example, the high-density regions at the cores of dense clusters are known to suppress star formation. It has been suggested that galaxy transformation occurs largely in groups, which are the intermediate step in density between field and cluster environments. In this paper, we use deep MIPS 24 μm observations of intermediate-redshift (0.3 ≲ z ≲ 0.55) group and field galaxies from the Group Environment and Evolution Collaboration (GEEC) subset of the Second Canadian Network for Observational Cosmology (CNOC2) survey to probe the moderate-density environment of groups, wherein the majority of galaxies are found. The completeness limit of our study is log(L_{TR}(L_⊙)) ≳ 10.5, corresponding to SFR ≳ 2.7 M_⊙ yr⁻¹. We find that the group and field galaxies have different distributions of morphologies and mass. However, individual group galaxies have star-forming properties comparable to those of field galaxies of similar mass and morphology; that is, the group environment does not appear to modify the properties of these galaxies directly. There is a relatively large number of massive early-type group spirals, along with E/S0 galaxies, that are forming stars above our detection limit. These galaxies account for the nearly comparable level of star-forming activity in groups as compared with the field, despite the differences in mass and morphology distributions between the two environments. The distribution of specific SFRs (SFR/M_*) is shifted to lower values in the groups, reflecting the fact that groups contain a higher proportion of massive and less active galaxies. Considering the distributions of morphology, mass, and SFR, the group members appear to lie between field and cluster galaxies in overall properties.

Key words: galaxies: evolution – galaxies: photometry – infrared: galaxies

Online-only material: color figures

1. INTRODUCTION

In a ΛCDM (Λ-cold dark matter) universe, galaxies, on average, move from areas of lower density to areas of higher density, merging and combining to form larger and larger systems like the massive galaxy clusters we see in the local universe. Galaxy evolution, therefore, cannot be understood without considering the influence of environment on galaxy properties. The importance of environment on galaxy evolution is demonstrated by the differences between galaxies in clusters and those in the field. For example, the fraction of blue galaxies in clusters has been decreasing since z ≳ 1, and local clusters are dominated by red galaxies (Butcher & Oemler 1978; Kennicutt 1983; Hashimoto et al. 1998; Andreon et al. 2004; Poggianti et al. 2006; Cooper et al. 2007; Loh et al. 2008; Cucciati et al. 2010). Dressler (1980) found a dramatic increase in the proportion of early-type galaxies with local density inside rich clusters, i.e., the morphology–density relation. This relation has also been shown to extend down to the group environment (Postman & Geller 1984). Most of these cluster early-type galaxies have not had appreciable star formation in gigayears, though as we move outward from the centers of the clusters, we see more late-type galaxies overall and more early–type galaxies that have had more recent star formation (Balogh et al. 1997, 1999; Bai et al. 2009).

Environment is expected to influence the rates of both gas exhaustion and interactions. The drop in star-forming activity in dense environments might be due to interactions with the intergalactic gas, such as through ram-pressure stripping of cold gas in galaxies (Gunn & Gott 1972; Larson et al. 1980; Kinney et al. 2004) or stripping of the hot gas through strangulation (Balogh et al. 2000; Kawata & Mulchay 2008; McCarthy et al. 2008). Alternatively, the lower fraction of star-forming galaxies might arise through galaxy–galaxy interactions, either major mergers or harassment (frequent high-speed encounters of galaxies that do not lead to mergers), both of which would accelerate the star formation and lead to early exhaustion of the interstellar material. Tides raised by the overall gravitational potential of dense clusters may also play a role (Henriksen & Byrd 1996). It has been proposed that the morphological transformation into early-type galaxies may occur first, suppressing star formation by stabilizing the gas against fragmentation (Martig et al. 2009), although other recent studies question this claim (Kovač et al. 2010).

Explaining the behavior of galaxies in different environments in terms of consistent theories for the growth of galaxies in the early universe has proven challenging (Bower et al. 2006; Kaviraj et al. 2009). Therefore, an intense observational approach is needed to help develop an understanding of the relation between environment and galaxy evolution. It should be possible to disentangle environmental influences by comparing galaxy behavior in different environments, though just as the mechanisms for galaxy transformation are not fully understood, the environments where these processes operate also need to be
explored and defined. Additionally, most of the previous work regarding star formation with respect to environment focused on rich clusters (e.g., Dressler et al. 2009; Bai et al. 2009; Haines et al. 2009, and references therein); relatively few studies have focused on groups (e.g., Zabludoff & Mulchaey 1998, 2000; Balogh et al. 2004; Johnson et al. 2007; Marcillac et al. 2008; Bai et al. 2010).

Simard et al. (2009) argue that cluster-centric processes are not the dominant factor in galaxy morphological transformation. The majority of galaxies live in the less-dense group environment (Geller & Huchra 1983; Eke et al. 2004), and because clusters probably form from coalescing groups and field galaxies, much of the evolution apparent in cluster galaxies may have occurred in groups prior to their assimilation into clusters. Zabludoff & Mulchaey (1998) found that the proportion of early-type galaxies in groups ranged from that typical of the field (∼25%) to that found in dense clusters (∼55%), suggesting that much of the morphological transformation of galaxies from field to cluster properties occurs in groups. Just et al. (2010) show that an increase in the proportion of SO galaxies with decreasing redshift occurs in moderate-mass groups/poor clusters (σ < 750 km s⁻¹), and Wilman et al. (2009) find that for groups at intermediate redshifts, the fraction of S0s is as high as in clusters, even at fixed luminosities. Additionally, because most galaxies reside in groups—and, therefore, galaxies spend most of their time in groups—uncovering the effects of these lower-density environments can help us understand the evolutionary path of the global galaxy population over cosmic time (McGee et al. 2009).

If morphological transformations frequently occur at intermediate densities, is this also the location where star formation is cutoff? Previous studies of star formation in groups have mostly focused on optical indicators such as Hα or [O II] λ3727 emission lines or ultraviolet continuum. These measures can extend to low levels of star formation, and they indicate a significantly lower level of activity in groups and clusters than in the field (Wilman et al. 2005a; Gerke et al. 2007; Balogh et al. 2009; Iovino et al. 2010; Peng et al. 2010). Such first-order comparisons are usually made under the assumption that the extinction is similar in groups and clusters (and that star formation is not deeply obscured). However, corrections are required to convert these optical indicators to accurate star formation rates (SFRs). At z ≥ 0.3, Hα moves out of the range of optical spectroscopy and SFR estimates rely on [O II], where the extinction is large and uncertain. The [O II] λ3727 line has additional problems of being sensitive to dust reddening and metallicity, thus being relatively weak in high-mass systems, although empirical corrections have been suggested to correct for this and other effects (Moustakas et al. 2006; Gilbank et al. 2010).

The infrared (IR) is advantageous for probing high levels of star formation. While SFRs determined in the IR are only sensitive to dust-obsured star formation, the correction to the total star formation in objects at moderate to high luminosities (L_{IR} ≥ 1 × 10^{10} L_⊙) is small (Rieke et al. 2009). Nonetheless, previous IR studies have not reached consistent conclusions about star formation in groups. Marcillac et al. (2008) found no significant dependence on the incidence of luminous infrared galaxies (LIRGs) as a function of field or group environment at z ∼ 0.8. At lower redshifts, Wilman et al. (2008) find a dearth of star formation in group galaxies at z ∼ 0.4, while Tran et al. (2009) find a similar incidence of SFRs in massive groups (for galaxies forming stars >3M_⊙ yr⁻¹) as in the field at z ∼ 0.37. For local groups, Bai et al. (2010) report rates of star formation somewhat lower than in the field (by ∼30%).

This paper is a step toward understanding the influence of the group environment on star formation and resolving some of the apparent discrepancies in previous studies of the same topic. Some of these discrepancies, especially in cluster studies, may arise from “field” samples contaminated by groups. To compare groups with actual field galaxies, we need a clean field sample with as many galaxies as possible. Here, we present 24 μm measurements of 232 group galaxies and 236 field galaxies from 0.3 ≤ z ≤ 0.55 in the Second Canadian Network for Observational Cosmology (CNOC2) survey.

The paper is organized as follows. In Section 2, we discuss the sample, data reductions, and errors. Section 3 covers the construction of fractional IR luminosity functions (LFs) and compares the IR luminosities, morphologies, and masses of group and field galaxies to estimate what effect (if any) environment has on star formation at these redshifts. We discuss the implications of our results in Section 4. For all cosmological corrections, we assume the parameters H_0 = 70 km s⁻¹ Mpc⁻¹, Ω_M = 0.3, Ω_Λ = 0.7.

2. SAMPLE AND DATA REDUCTION

2.1. Sample Selection and Photometry

The CNOC2 survey is a photometric and spectroscopic survey of faint galaxies covering more than 1.5 deg² over four widely spaced patches of sky (Yee et al. 2000; Carlberg et al. 2001a). The original survey included five-color photometry in I_C, R_C, V, B, and U to R_C ∼ 23.0 (Vega) mag and spectroscopic redshifts (to R_C ∼ 21.5 mag) for an unbiased sample of ∼6000 galaxies with the purpose of studying galaxy clustering, dynamics, and evolution at intermediate redshifts (0.1 ≤ z ≤ 0.6). The survey is spectroscopically incomplete, but the selection function is very well defined for this redshift range (Lin et al. 1999; Yee et al. 2000).

The groups themselves were originally selected by using a friends-of-friends algorithm to find overdensities of galaxies in three-dimensional space (Carlberg et al. 2001a, 2001b). Follow-up LDSS2 spectroscopy (to R_C ∼ 22.0) targeted 26 of these Carlberg groups at 0.3 ≤ z ≤ 0.55, creating a sample of group and field galaxies to a greater depth than the original sample, with increased and unbiased spectroscopic completeness (Wilman et al. 2005b). Additional group members were carefully selected to ensure that the resulting sample would be unbiased with regard to color using the method outlined in Wilman et al. (2005a). This subset of the original CNOC2 survey—26 groups at 0.3 ≤ z ≤ 0.55 to R_C ∼ 22.0—was followed up by the Group Environment and Evolution Collaboration (GEEC), and hereafter, we refer to these as the GEEC groups. Visual (Wilman et al. 2009) and automated (McGee et al. 2008) morphological classifications were made using deep, high-resolution Hubble Space Telescope (HST) Advanced Camera for Surveys (ACS) images of the same 26 groups (Wilman et al. 2009). Additional multiband coverage includes Galaxy Evolution Explorer UV (McGee et al. 2011) and IRAC (Balogh et al. 2007, 2009; Wilman et al. 2008). X-ray properties of a subset of the groups have been measured with XMM-Newton and Chandra observations (Finoguenov et al. 2009).

We present observations of these GEEC groups (as defined by Wilman et al. 2005a) using the MIPS 24 μm band on the Spitzer Space Telescope (Rieke et al. 2004). We used MIPS in single-source photometry mode (field of 5' × 5') due to the...
compact nature of the groups, and long exposure times allowed us to detect relatively low SFRs (<10 $M_\odot$ yr$^{-1}$). All but five of the groups have either complete coverage of their members with MIPS or are only missing one or two member galaxies. All galaxies assigned to groups using the algorithm described by Wilman et al. (2005a) and within the MIPS field of view are considered group members in this paper. The MIPS 24 $\mu$m field of view corresponds to ~1.3 Mpc (~2 Mpc) on a side at $z = 0.3$ (0.55).

The data from these observations were reduced using version 3.10 of the MIPS Data Analysis Tool (Gordon et al. 2007). Fields with overlapping regions were mosaicked for better coverage near the image edges. Sources 3$\sigma$ above the standard deviation of the background were identified using DAOFIND in the IRAF7 environment. Flux densities were calculated using a point-spread function (PSF) made from bright sources in one of the larger mosaicked fields and the IRAF PSF-fitting routine ALLSTAR, correcting for flux lost in the wings of the PSF as described by the Spitzer Science Center.8

Our initial field sample consisted of all galaxies not identified as residing in a group. Given the completeness of the group sample, it has been estimated that ~21% of this field sample is contaminated by unidentified groups (Carlberg et al. 2001a; McGee et al. 2008). To reduce the amount of group contamination in the field, we plotted a running-average histogram of redshifts for the LDSS2 pencil-beam fields with a bin size of $z = 0.001$. Any galaxies that fall in a bin with five or more galaxies at any point in the running average were removed from the field sample as possible group contaminants. This method will obviously remove some true field galaxies, as it does not account for the spatial positions of the possible group galaxies; however, this is a quick, simple method for removing galaxies that are likely to live in groups. We removed a total of 78 galaxies—or ~25%—of our original field sample.

These observations of groups and the “cleaned” field sample (referred to simply as the “field” from this point on) result in 24 $\mu$m measurements or upper limits for 232 group galaxies and 236 field galaxies from $0.3 \lesssim z \lesssim 0.55$, of which 79 group galaxies and 65 field galaxies are detected. Our absolute detection limit (3$\sigma$) is 119 $\mu$Jy, corresponding to the 24 $\mu$m observations with the highest background. These observations result in a detection limit for the groups of $L_{\text{TIR}} \sim 3.5 \times 10^{10} L_\odot$ (SFR $\sim 3.3 M_\odot$ yr$^{-1}$), where $L_{\text{TIR}}$ is the total IR luminosity as defined by Rieke et al. (2009). However, only two groups (20 galaxies) have detection limits at this level; ~91% of our group sample (and ~93% of the field sample) have 24 $\mu$m coverage to a lower detection limit: $L_{\text{TIR}} \sim 2.9 \times 10^{10} L_\odot$ (SFR $\sim 2.7 M_\odot$ yr$^{-1}$). We use this lower value as our detection limit for the rest of the paper. At a typical redshift for our groups ($z \sim 0.43$), $L_{\text{TIR}}^* \propto SFR \sim 10 M_\odot$ yr$^{-1}$ (Rujopakarn et al. 2010). The typical optical surface density of the GEEC groups is ~3 galaxies Mpc$^{-2}$ for galaxies with $M_B < -20$, though it ranges from ~1 to ~6.5. Cluster surface densities can range from these values in the outskirts to as high as several hundred galaxies Mpc$^{-2}$ in the dense cores (Dressler 1980).

2.2. Uncertainties and Reliability

We cross-correlated the sources detected at 24 $\mu$m (almost 2000 objects over all fields) with the GEEC spectroscopic catalog to within 3 arcsec; if multiple optical sources were located within 3 arcsec of a 24 $\mu$m source, the nearest optical source was used (only 20 instances of such multiple matches using the entire 24 $\mu$m and CNOC2 catalogs were recorded). Any GEEC galaxy not matching this criterion was given a 3$\sigma$ upper limit. To estimate the 1$\sigma$ errors (and 3$\sigma$ upper limits for non-detected sources) in the 24 $\mu$m flux densities, we put down apertures in blank areas of the fields and took the standard deviation of the nearest 20 background apertures to a given source.

Because of the depth of our observations and the size of the MIPS 24 $\mu$m PSF, it is necessary to know the fraction of false detections—in other words, the fraction of 24 $\mu$m sources incorrectly attributed to an optical source in our catalog. We therefore placed a random number of fake sources (up to 300 sources per pointing, which at $z = 0.55$ equates a surface density of $4$ Mpc$^{-2}$) on each image and matched the 24 $\mu$m detections to both the fake source catalog and our GEEC spectroscopic catalog. We use three different match radii—4, 3, and 2.5 arcsec—and found the mean fraction of false detections to be 3.1%, 1.8%, and 1.3%, respectively, for each match radius. As expected, the number of false detections per unit area is relatively constant and does not change significantly for each match radius. We could use any of the listed match radii and not change the number of false matches substantially (i.e., from ~3 to ~7 for the group and field samples individually, out of ~230 galaxies in each environment, and from ~2 to ~5 for the cleaned field). However, if we use too small a match radius ($\lesssim 2.5$ arcsec), we risk eliminating real matches. At our typical detection levels of $\sim 4\sigma - 5\sigma$, the r.m.s. positional errors at 24 $\mu$m are $\sim 1.5$ arcsec. Additionally, from examination of our HST ACS images (see the Appendix for more information), we discovered that using a matching radius of 4 arcsec could introduce more false detections than anticipated due to the crowded nature of our group-dominated fields. For these reasons, we used the 3 arcsec matching radius. A 3 arcsec matching radius results in ~4.2 incorrectly matched galaxies for the groups and ~2.7 for the cleaned field for all galaxies. If we assume that all of the mismatched galaxies are detected at 24 $\mu$m, we would have upper limits that $\lesssim 5.6\%$ and $\lesssim 6.5\%$ of detected group and field galaxies, respectively, are incorrectly matched.

We also need to keep in mind that we are comparing group and field galaxies en masse, not individually. False detections will affect the groups and field each the same way, and so will not bias our results provided that the number of false detections remains low, which we have already shown to be the case. As such, the matching technique (and match length of 3 arcsec) is sufficient for our purposes.

3. IR PROPERTIES OF SAMPLE GALAXIES

Extreme environments, such as the interior regions of clusters, clearly quench star formation in galaxies and reduce their IR outputs (e.g., Bai et al. 2009). Based on the ages of their dominant stellar populations and distributions of morphologies, galaxies in rich groups and clusters must have a similar evolution, at least at low redshift (Balogh & McGee 2010). This suggests that galaxy transformation occurs in groups as well as in clusters. To test for such behavior, we compare the fractional IR LF in groups with that of field galaxies at intermediate redshifts.

---

7 IRAF is distributed and supported by the National Optical Astronomy Observatories (NOAO).
8 The Spitzer Science Center (http://ssc.spitzer.caltech.edu) is supported by NASA, the Jet Propulsion Laboratory, the California Institute of Technology, and the Infrared Processing and Analysis Center.
To compare the IR output and SFR of group and field galaxies, we estimated the SFR and total IR luminosity ($L_{\text{TIR}}$) from the $24\,\mu\text{m}$ flux densities using the method described by Rieke et al. (2009), who use Spitzer data to create a group of luminous star-forming galaxy templates more complete in the near- and mid-IR than previous templates.

Our method for determining SFR and $L_{\text{TIR}}$ is only accurate for purely star-forming galaxies. Obscured active galactic nuclei (AGNs) can also emit a significant fraction of their light in the mid-IR. To identify possible AGN contaminants in our sample, we compared our $24\,\mu\text{m}$ detected galaxies with Chandra detections. Four of the galaxies in the CNOC2 sample were identified as AGNs with clear X-ray detections, though all four were field galaxies outside of our redshift range (i.e., not in our GEEC sample). However, some AGNs may be so buried that we are not able to detect them at our current X-ray detection threshold. More importantly, slightly less than half of the groups targeted by MIPS have X-ray coverage, so there may still be some AGNs contaminating our sample. Given the few AGNs detected with the existing data and in previous studies of AGN activity in groups (Dwarakanath & Nath 2006; Silverman et al. 2009), we expect this number to be small.

To correct for the different redshifts of our group and field galaxies, we used the derived luminosity evolution of IR galaxies from Le Floc’h et al. (2005), who show that IR galaxies as a whole evolve in luminosity as $(1+z)^{3.2}$ from $z \sim 0$ to $z \sim 1.2$. We evolved our group and field galaxy IR luminosities to a fiducial redshift ($z = 0.5$) to remove redshift bias in our sample. This IR luminosity evolution is for all IR galaxies regardless of environment; however, the Le Floc’h et al. (2005) sample (as for most field samples) is expected to be $\sim 50\%$ groups, $\sim 50\%$ true field galaxies, making this model reasonable for our purposes. This conclusion is supported by the lack of significant differences in the field and group fractional luminosity functions (fLFs) as discussed below.

3.1. Methodology

3.2. Results for IR-active Galaxies

3.2.1. IR Luminosities and Star Formation Rates

In Figure 1, we present $L_{\text{TIR}}$ (left axis) and SFR (right axis) with respect to redshift for all galaxies in the CNOC2 survey for which we have MIPS $24\,\mu\text{m}$ detections. Group galaxies are shown as solid red circles, while field galaxies are open blue circles, and the X-ray-identified AGNs are overplotted as green triangles. The average detection limit for all of our $24\,\mu\text{m}$ fields is shown by the solid black curve; the redshift limits of our GEEC group and field sample are denoted by dashed lines ($0.3 \lesssim z \lesssim 0.55$). The group and field IR-active populations do not appear significantly different.

Figure 2 gives us a clearer picture of the group and field populations in terms of $L_{\text{TIR}}$. We plot histograms of the normalized distributions of $L_{\text{TIR}}$ (which we will refer to as fLFs from here on) for the group and field galaxies (red filled circles and blue open circles, respectively). The dashed line indicates our $24\,\mu\text{m}$ detection limit for all field galaxies, while the dotted line is the detection limit for all group galaxies. The fractions in each bin (y-axis values) are normalized by the number of $24\,\mu\text{m}$ detected galaxies in each environment and corrected for spectroscopic incompleteness as a function of magnitude. Weights were computed using the method outlined in Appendix A of Wilman et al. (2005a), except in this case we do not correct for any radial dependent selection, which tends to overweight galaxies on the outskirts of groups.

We have also corrected for completeness with respect to the $24\,\mu\text{m}$ data. We calculated the $24\,\mu\text{m}$ incompleteness by estimating the SFR corresponding to the detection limits for all galaxies in each image. We then found the fraction of group and field galaxies (separately) with SFR detection limits below a given SFR; the inverse of this fraction in each bin corresponds to our $24\,\mu\text{m}$ completeness weighting. The completeness corrections for the points shown above both of these limits are small: factors of $\lesssim 1.7$ for both the group and field galaxies.
The group and field galaxy ILFs are identical within the error bars up to \( \log(L_{\text{TIR}}(L_\odot)) \sim 12 \). The last two bins contain few galaxies, so we cannot compare the bright end with much certainty. The measurements slightly below our detection limit should not be significantly biased given the care to avoid bias in the sample selection (Wilman et al. 2005a) and that the vast majority of the group and field galaxies have detection limits below the indicated limit; therefore, we can say that these data also agree within the error bars with some certainty. Overall, the ILFs suggest that there is little difference between the groups and the field (with respect to \( L_{\text{TIR}} \)). Given that there are similar numbers of spectroscopically identified galaxies in the groups and field in this redshift range, even the overall normalization will be the same. This seems to indicate that the group environment is not responsible for suppressing or enhancing star formation among the actively star-forming population. To confirm the apparent similarity of the group and field samples, we performed a two-sample Kolmogorov–Smirnov (K-S) test on the unbinned ILFs (the raw \( L_{\text{TIR}} \) and \( 1\sigma \) error bars for groups in three different bins. The total IR luminosity for individual group galaxies does not depend on the size of the group. In other words, we see no trend in star formation levels with group richness.

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

The group and field galaxy ILFs are identical within the error bars up to \( \log(L_{\text{TIR}}(L_\odot)) \sim 12 \). The last two bins contain few galaxies, so we cannot compare the bright end with much certainty. The measurements slightly below our detection limit should not be significantly biased given the care to avoid bias in the sample selection (Wilman et al. 2005a) and that the vast majority of the group and field galaxies have detection limits below the indicated limit; therefore, we can say that these data also agree within the error bars with some certainty. Overall, the ILFs suggest that there is little difference between the groups and the field (with respect to \( L_{\text{TIR}} \)). Given that there are similar numbers of spectroscopically identified galaxies in the groups and field in this redshift range, even the overall normalization will be the same. This seems to indicate that the group environment is not responsible for suppressing or enhancing star formation among the actively star-forming population. To confirm the apparent similarity of the group and field samples, we performed a two-sample Kolmogorov–Smirnov (K-S) test on the unbinned ILFs (the raw \( L_{\text{TIR}} \) and \( 1\sigma \) error bars for groups in three different bins. The total IR luminosity for individual group galaxies does not depend on the size of the group. In other words, we see no trend in star formation levels with group richness.

(A color version of this figure is available in the online journal.)
We investigate SFR with respect to stellar mass in Figures 4 through 6. Figure 4 shows SFR plotted with respect to stellar mass for the group (red filled circles) and field (blue open circles) galaxies. Only galaxies above our 24 μm detection limit, which is shown by the dashed line. The black filled triangles (black open triangles) are the mean SFR for the groups (field) in three mass bins above log(M_∗(M_⊙)) = 10. The field and group galaxies have different distributions. The solid line represents the trend found by Noeske et al. (2007) for 24 μm identified “field” galaxies at 0.2 ≤ z ≤ 0.7 (plotted here at an arbitrary normalization). Because Noeske et al. (2007) did not distinguish between group and field galaxies, their trend is likely a combination of the two environments. (A color version of this figure is available in the online journal.)

In Figure 5, we plot a “specific SFR function” (SFR/M_∗) in the same manner as Figure 2, though only including galaxies with SFR ≥ 2.7 M_⊙ yr⁻¹. Each histogram has been normalized so that its total value is 1. The groups have more galaxies at higher masses than their field counterparts, resulting in lower specific SFRs for the groups. This difference is not highly significant, however: a two-dimensional K-S test results in a 27% probability that these two data sets come from the same distribution. (A color version of this figure is available in the online journal.)

Figure 6 compares stellar mass and SFR in a slightly different way. The top plot shows the fraction of 24 μm detected field and group galaxies as a function of specific SFR (sSFR) with log(M_∗(M_⊙)) < 10.5, labeled as blue dashed and red solid
and 6 may be showing the beginning stages of suppression of star formation in the groups. The subtle trends seen in Figures 5 of higher-mass group galaxies having significantly lower SFRs than in the top plot: the groups have galaxies forming stars at this high rate at a variety of masses, while the field galaxies peak at $\log(M_\ast(M_\odot)) \sim 11$. This may be another indication of a stronger mass–SFR relation in the field than the group galaxies, though the significance is small.

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

Figure 7. Fractions of low- and high-activity galaxies with respect to environment. The top plot shows the fraction of galaxies with SFR $< 2.7 M_\odot$ yr$^{-1}$ normalized by the total number of galaxies in each environment, respectively, per mass bin. For stellar masses below $\sim 11.5$, the groups and the field are nearly identical; above this limit, however, the groups have a few massive, low-activity galaxies while the field has none. (This is not significant, as there are only three galaxies in the two highest mass bins for the groups.) The bottom plot shows the fractions of galaxies with SFR $> 10 M_\odot$ yr$^{-1}$ for each environment, respectively. We see a stronger difference between the group and field galaxies here than in the top plot: the groups have galaxies forming stars at this high rate at a variety of masses, while the field galaxies peak at $\log(M_\ast(M_\odot)) \sim 11$. This may be another indication of a stronger mass–SFR relation in the field than the group galaxies, though the significance is small.

We performed a Monte Carlo analysis of the data in the top plot of Figure 7 to estimate whether the overall fraction of low-activity galaxies, at constant stellar mass, is significantly higher for group galaxies. We found the total number of group galaxies per mass bin and randomly selected the same number of galaxies per mass bin from the field, making a fake group sample. We then made the same plot as the top part of Figure 7 using the fake group galaxies: the fraction of fake low-activity galaxies is of low significance. The fake group galaxies have lower relative SFRs. A two-sample K-S test results in a $\sim 3\%$ probability that the low-mass ($\log(M_\ast(M_\odot)) < 10.5$) group and field galaxies come from the same parent sample and a $\sim 89\%$ probability for the high-mass group and field galaxies ($\log(M_\ast(M_\odot)) > 10.5$). While neither of these cases indicate a $3\sigma$ result, it makes sense given Figure 4, which shows a trend of higher-mass group galaxies having significantly lower SFRs as compared with the field. The subtle trends seen in Figures 5 and 6 may be showing the beginning stages of suppression of star formation in the groups.

In Figure 7, we split our group and field galaxies in terms of their SFRs with respect to stellar mass. The top plot shows the fraction of what we call “low-activity” galaxies (SFR $< 2.7 M_\odot$ yr$^{-1}$) normalized by the total number of galaxies per mass bin in the groups (red solid line) and field (blue dashed line). The two highest mass bins in the groups house a total of three galaxies, all of which are in groups with 10 or fewer members, so any trend in the number of low-activity, high-mass group galaxies does not appear to be significant. As a result, the group and field galaxies are similar in terms of the fraction of low-activity galaxies for a given stellar mass. The bottom plot shows the fraction of galaxies in each environment with SFR $> 10 M_\odot$ yr$^{-1}$ with the same normalization as the top plot. We do potentially see a stronger difference between the group and field galaxies at these higher SFRs: the groups have galaxies forming stars at this high rate at a variety of masses, while the field galaxies peak at $\log(M_\ast(M_\odot)) \sim 11$. This may be another indication of a stronger mass–SFR relation in the field than in the groups, though the differences between the group and field galaxies here are of low significance.

Another way to describe these results is that, if we use the field mass–SFR relation to determine the expected IR luminosity distributions in groups, we would conclude that the groups are slightly underluminous because of their higher proportion of high-mass galaxies. Marcillac et al. (2008) study the environment of $0.7 \leq z \leq 1.0$ LIRGs and ultraluminous IR galaxies (ULIRGs), and they find that, at similar masses, 32% of
all the galaxies in their sample reside in groups, and 32% of their LIRGs and ULIRGs also reside in groups. Where we find a small and barely significant difference, their study indicates none. That is, this reinforces our conclusion that the group environment does not suppress or enhance star formation in the galaxies as a whole. Though we do see indications of suppression in the groups when we compare sSFRs, the difference is subtle and might depend on the low-mass regime where we are incomplete (galaxies with lower SFRs than we were able to detect with MIPS), or other variables.

3.2.3. Morphologies

Another parameter subject to transformation in dense environments is galaxy morphology. Is there any difference in morphology types with respect to star formation between the group and field galaxies? Wilman et al. (2009) report on the visual morphologies of the GEEC groups and field galaxies using high-resolution ACS data. They find that the two environments tend to harbor different types of galaxies: S0 galaxies are more prevalent in groups than in the field at a fixed luminosity, indicating that suppression of star formation and bulge growth have been more common in the group environment. Overall, for galaxies brighter than $M_r = -21$, they find that the groups have about 1.5 times the number of E/S0 galaxies as the field (Wilman et al. 2009).

We compared the visual morphologies with our IR SFRs using the Wilman et al. (2009) classifications. Thus, “early-type spirals” (eSps) are galaxies classified as Sa through Sbc (including barred spirals), and “late-type spirals” (lSps) are classified as Sc through Sm (including barred spirals). The fractions of IR-detected galaxies with optical classifications (both groups and the field) are as follows: 13% of ellipticals, 10% of S0s, 60% of eSps, 33% of lSps, 15% of irregulars, 17% of mergers, and 61% of galaxies identified as “peculiar.” It is perhaps a surprise that eSps are twice as likely to be detected at 24 $\mu$m as lSps, but this difference may arise because of the lower masses of the later galaxy types.

These conclusions can be tested with quantitative morphology metrics, such as the concentration, asymmetry, clumpiness method (Abraham et al. 1994, 1996; Conselice 2000, 2003; see also McGee et al. 2008 for other methods). At $z \sim 0.5$, surface brightness dimming might become a problem when identifying spirals, particularly late types, as the fainter spiral features become indistinguishable from the background. Shi et al. (2009) have shown how to correct concentration and asymmetry (referred to as CA from now on) for the effects of surface brightness dimming to provide unbiased metrics at and above the redshifts of our groups. We have used their methodology to calculate CA for our sample of field and group galaxies, as shown in Figure 9 (small black dots). In the top plot, the average values (and error bars) for the groups and field galaxies are given by the red square and blue star, respectively. The dashed line is an arbitrary division roughly separating early- and late-type galaxies that we discuss below. Consistent with Wilman et al. (2009), our results indicate a tendency for group galaxies to have, on average, a higher concentration and lower asymmetry (indicative of E and S0 galaxies) than in the field.

Of 144 galaxies detected at 24 $\mu$m, seven are Es and four are S0s. Three of the galaxies are classified as “peculiar,” which means they have been visually identified as either having an interacting neighbor or a morphology slightly disturbed from the given classification, and one galaxy is listed as an S0/Sa (most likely an S0 but also has Sa qualities). Still, it is unusual to find any E or S0 galaxies with SFRs at these levels. To be certain the early-type galaxy detections are robust, we investigated other possibilities for the IR emission.

The first issue concerns our source matching: is it possible that there are nearby (projected) neighbors that are being mismatched with the E/S0 galaxies? As discussed in the Appendix, inspection of the ACS images shows that a few of the early-type galaxies have close neighbors, making identifying which galaxy in the field of view is responsible for the IR emission difficult. To be conservative, we rejected any early-type galaxies where the IR emission could be coming from another object. After removing these ambiguous E/S0 detections, we were left with four ellipticals and two S0s firmly detected at 24 $\mu$m. We also double-checked our matching of the 24 $\mu$m positions with the IRAC 3.6 $\mu$m coordinates. Four of the six E/S0 galaxies have IRAC coverage, and all of them match the IRAC coordinates within 1.5 arcsec or less. Because we have imposed very stringent requirements to claim a detection, six detected E/S0 galaxies represent a lower limit.
As a double check on the morphologies, we again plot asymmetry and concentration for all galaxies with CA values (small, black circles) and the six IR-active early-type galaxies (red circles for ellipticals and black triangles for S0s, with filled points indicating a group galaxy and empty points indicating a field galaxy) at the bottom of Figure 9. All six galaxies fall in the “early-type” area of the plot, and they also all fall well under our early-/late-type dashed line. It appears that these six E/S0 galaxies are indeed early types with bright 24 μm emission.

There is one other culprit that could be masquerading as star formation, however: AGNs. Of the six early-type galaxies with confirmed IR emission, only two have X-ray coverage, though neither of them are detected down to $L_X \sim 10^{31}$ erg s$^{-1}$ (J. Mulchaey et al. 2011, in preparation). As an additional test for AGNs, we look to the IRAC data. The intersection of the stellar light and the warm/cold dust components produces a dip in the SED at rest frame $\sim 5$ μm for normal star-forming galaxies. Buried AGNs heat the dust to higher temperatures, which “fills in” this dip. If our IR-detected early-type galaxies have similar colors at IRAC wavelengths to the typical galaxies in our sample, then AGNs are probably not contributing significantly to the mid-IR emission. In Figure 10, we plot IRAC [3.6]–[4.5] and [3.6]–[5.8] versus redshift for all galaxies with IRAC coverage in our sample. Most of the galaxies fall into a narrow color range in both plots, indicating that we are probing the Rayleigh–Jeans tail of the stellar bump. If the 24 μm emission were dominated by an embedded AGN, these colors would be more positive due to the warm dust filling in the “dip” in the SED, causing the SED to brighten as we move through the IRAC bands. None of the early-type galaxies detected at 24 μm (with IRAC coverage) show the signature of an AGN in the IRAC colors.

Two of our six IR-bright early-type galaxies do not have X-ray or complete IRAC coverage. We have enough SED coverage of one of these two to make out some of the stellar bump and the increase in dust emission in the IR, which seems to indicate star formation instead of an AGN, but it is difficult to say with certainty. The other source has too few photometric data points to make any solid conclusion; however, given the lack of AGNs we have found so far in our entire sample, it seems that AGNs are a rarity. While we cannot be certain that these two galaxies do not host AGNs, it seems unlikely.

Even, by these stringent tests, we have detected four elliptical and two S0 galaxies at 24 μm, none of which have an obvious AGN contribution. Five of these galaxies (three ellipticals and two S0s) are in groups. We cannot tell whether the groups and field are different in this regard at a statistically significant level. However, among the IR-detected group members, ≥6% are early types. That is, some early-type galaxies in groups were forming stars at significant levels around $z \sim 0.5$. We can compare this behavior with that of local early-type galaxies using the study of Devereux & Hameed (1997). They extracted IRAS 60 μm detections of galaxies in the Nearby Galaxies Catalog (Tully 1989), which contains 2367 galaxies within 40 Mpc ($H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$). After eliminating ones not covered by IRAS or compromised for other reasons, 2094 remained in this study, of which 1215 were detected by IRAS (including 22% of the 151 ellipticals). We determined the 99th percentile of 60 μm luminosity for the E–E/S0 and S0–S0/a categories and converted it to $L_{\text{TIR}}$ of 2.4 × 10$^9$ $L_\odot$ and 2.3 × 10$^{10}$ $L_\odot$, respectively. The corresponding SFRs are 0.27 and 2.6 $M_\odot$ yr$^{-1}$ (Rieke et al. 2009) and are indicated in Figure 11 by dashed and dotted lines, respectively. Figure 11 also shows stellar mass versus SFR for all galaxies in our sample detected at 24 μm (small black dots), separated by environment, with visual morphologies indicated by a variety of symbols. The SFRs for the two group S0 galaxies are at or just below the 99th percentile for local S0–S0/a galaxies, while the SFRs of all four E galaxies exceed the 99th percentile for local E–E/S0 galaxies by factors of 3–20, an unexpected result given that there are less than 100 early-type group members in our sample.

On a more general note, these measurements imply that not all early-type galaxies are dead at $z \sim 0.5$; many are still in the process of forming stars, indicating a larger amount of evolution with redshift than previously thought (e.g., Larson 1974; Chiosi & Carraro 2002). While it does appear that there are still some early-type galaxies forming stars in the local universe (Temi et al. 2009), the ubiquity of IR-active early types in group and field environments remains largely unknown. We do know, however, that star formation in E/S0 galaxies has been decreasing since $z \sim 1$. Kaviraj et al. (2008) find that star formation in early-type galaxies has decreased by <50% since $z \sim 0.7$, and they show that local early-type galaxies, while largely quiescent now, have had spurts of star formation in their recent past. Thus, the enhancement of star-forming activity in early-type galaxies at $z \sim 0.5$ compared with the present epoch may apply generally for field and group members.

We now discuss the fraction of 24 μm detected galaxies with respect to the full range of morphologies, separated by groups and field. As just discussed, for E/S0 galaxies, 5 out of 75 in...
Marcillac et al. (2007), Patel et al. (2009), and Koyama et al. (2010) show that the densest galaxies in terms of star formation. Marcillac et al. (2007), Patel et al. (2009), who report that star-forming galaxies (defined by SFR $\gtrsim 0.2 M_\odot$ yr$^{-1}$) are much less likely to be found in the cores of local clusters Coma and A3266. Biviano & Katgert (2004) use kinematics of different cluster galaxy morphologies to show that lSps are more likely to be found at higher distances from the core.

Although the SFR suppression in cluster cores is clearly established, work to date has not reached a firm conclusion about the comparison of group galaxies with those in the field and in clusters with respect to the IR regime. Wilman et al. (2008) find, from 8 $\mu$m measurements of a subset of the GEEC sample, that the SFR is significantly suppressed in groups as compared with the field at $z \sim 0.4$. Bai et al. (2010) use 24 $\mu$m observations to show that local groups have somewhat suppressed SFRs compared with the field, and somewhat elevated ones compared with clusters (though they have a lower SFR limit than our study). At higher redshifts, Marcillac et al. (2008) use a large sample of galaxies in the Extended Groth Strip to find that LIRGs and ULIRGs measured at 24 $\mu$m do not preferentially exist in higher-density environments (including groups) at $z \sim 0.9$. Tran et al. (2009) use 24 $\mu$m data to find a substantially (four times) higher incidence of active star-forming galaxies in groups compared with clusters at $z \sim 0.37$. They also find that the groups and field are similar in this regard for their luminosity-limited sample. Patel et al. (2009) use 24 $\mu$m measurements to find a progressive suppression of the SFR by an order of magnitude from the field to cluster core densities.

Other recent studies in optical bands show suppression of star formation in groups due to different mechanisms. Peng et al. (2010) and Kovač et al. (2010) use Sloan Digital Sky Survey and zCOSMOS galaxies at a variety of redshifts (up to $z \sim 1$) and environments to show that the effects of environment on individual galaxies are separate from the evolution and quenching with increasing galaxy mass. This “mass quenching” is the dominant effect at high galaxy masses ($M_* \gtrsim 10^{10.2} M_\odot$), while other effects, like environmental quenching, dominate for low-mass and satellite galaxies ($M_* \lesssim 10^{10} M_\odot$; Peng et al. 2010). As mentioned previously, Tran et al. (2009) find comparable fractions of star-forming galaxies in their supergroup and the field for a luminosity-limited sample, but their mass-selected sample shows that the supergroup has about half the fraction of star-forming galaxies as the field.

In light of the uncertainties in the effects of groups on the SFRs as reflected in the Spitzer 8 and 24 $\mu$m data, we have carried out a thorough study of the CNOC2 groups at $0.3 < z < 0.55$, which are exceptionally well characterized and have substantial amounts of ancillary data. The large sizes of this group sample and of the accompanying field sample also allow reasonably good statistics for our conclusions. We find that the incidence of 24 $\mu$m emission is virtually the same in these groups as in the field. This result agrees well with that of Tran et al. (2009) for their luminosity-selected supergroup at $z = 0.37$ but has higher statistical weight because our field sample is of local clusters RXJ 1716.4+6708 and RXJ 0152.7-1357 strongly suppress star formation. Using the CNOC1 cluster galaxy sample (0.2 $\lesssim z \lesssim$ 0.55), Balogh et al. (2000) find that the mean galaxy SFR decreases with decreasing radius from the center of the cluster, and Ellington et al. (2001) shows a decrease in the fraction of blue and emission-line galaxies and an increase in the fraction of ellipticals as one approaches the cluster core. Similarly, for the more distant cluster MS 1054-03 ($z \sim 0.8$), Bai et al. (2007) observed that star formation in member galaxies near the core was substantially suppressed; Vulcani et al. (2010) find the same suppression in cluster galaxies from 0.4 $\lesssim z \lesssim$ 0.8 as compared with the field, though the reduction in SFR was more modest in those clusters. Locally ($z \lesssim 0.3$), we continue to see star formation quenched or suppressed near cluster cores: Haines et al. (2009) find suppression for star-forming cluster galaxies (defined by $L_{IR} > 10^{10} L_\odot$), as do Bai et al. (2006, 2009), who report that star-forming galaxies (defined by SFR $\gtrsim 0.2 M_\odot$ yr$^{-1}$) are much less likely to be found in the cores of local clusters Coma and A3266. Biviano & Katgert (2004) use kinematics of different cluster galaxy morphologies to show that lSps are more likely to be found at higher distances from the core.

4. DISCUSSION

There is strong agreement that the dense environments in the cores of clusters do have a large effect on their dense galaxies in terms of star formation. Marcillac et al. (2007), Patel et al. (2009), and Koyama et al. (2010) show that the densest regions of the clusters RXJ 1716.4+6708 and RXJ 0152.7-1357 strongly suppress star formation. Using the CNOC1 cluster galaxy sample (0.2 $\lesssim z \lesssim$ 0.55), Balogh et al. (2000) find that the mean galaxy SFR decreases with decreasing radius from the center of the cluster, and Ellington et al. (2001) shows a decrease in the fraction of blue and emission-line galaxies and an increase in the fraction of ellipticals as one approaches the cluster core. Similarly, for the more distant cluster MS 1054-03 ($z \sim 0.8$), Bai et al. (2007) observed that star formation in member galaxies near the core was substantially suppressed; Vulcani et al. (2010) find the same suppression in cluster galaxies from 0.4 $\lesssim z \lesssim$ 0.8 as compared with the field, though the reduction in SFR was more modest in those clusters. Locally ($z \lesssim 0.3$), we continue to see star formation quenched or suppressed near cluster cores: Haines et al. (2009) find suppression for star-forming cluster galaxies (defined by $L_{IR} > 10^{10} L_\odot$), as do Bai et al. (2006, 2009), who report that star-forming galaxies (defined by SFR $\gtrsim 0.2 M_\odot$ yr$^{-1}$) are much less likely to be found in the cores of local clusters Coma and A3266. Biviano & Katgert (2004) use kinematics of different cluster galaxy morphologies to show that lSps are more likely to be found at higher distances from the core.

Although the SFR suppression in cluster cores is clearly established, work to date has not reached a firm conclusion about the comparison of group galaxies with those in the field and in clusters with respect to the IR regime. Wilman et al. (2008) find, from 8 $\mu$m measurements of a subset of the GEEC sample, that the SFR is significantly suppressed in groups as compared with the field at $z \sim 0.4$. Bai et al. (2010) use 24 $\mu$m observations to show that local groups have somewhat suppressed SFRs compared with the field, and somewhat elevated ones compared with clusters (though they have a lower SFR limit than our study). At higher redshifts, Marcillac et al. (2008) use a large sample of galaxies in the Extended Groth Strip to find that LIRGs and ULIRGs measured at 24 $\mu$m do not preferentially exist in higher-density environments (including groups) at $z \sim 0.9$. Tran et al. (2009) use 24 $\mu$m data to find a substantially (four times) higher incidence of active star-forming galaxies in groups compared with clusters at $z \sim 0.37$. They also find that the groups and field are similar in this regard for their luminosity-limited sample. Patel et al. (2009) use 24 $\mu$m measurements to find a progressive suppression of the SFR by an order of magnitude from the field to cluster core densities.

Other recent studies in optical bands show suppression of star formation in groups due to different mechanisms. Peng et al. (2010) and Kovač et al. (2010) use Sloan Digital Sky Survey and zCOSMOS galaxies at a variety of redshifts (up to $z \sim 1$) and environments to show that the effects of environment on individual galaxies are separate from the evolution and quenching with increasing galaxy mass. This “mass quenching” is the dominant effect at high galaxy masses ($M_* \gtrsim 10^{10.2} M_\odot$), while other effects, like environmental quenching, dominate for low-mass and satellite galaxies ($M_* \lesssim 10^{10} M_\odot$; Peng et al. 2010). As mentioned previously, Tran et al. (2009) find comparable fractions of star-forming galaxies in their supergroup and the field for a luminosity-limited sample, but their mass-selected sample shows that the supergroup has about half the fraction of star-forming galaxies as the field.

In light of the uncertainties in the effects of groups on the SFRs as reflected in the Spitzer 8 and 24 $\mu$m data, we have carried out a thorough study of the CNOC2 groups at $0.3 < z < 0.55$, which are exceptionally well characterized and have substantial amounts of ancillary data. The large sizes of this group sample and of the accompanying field sample also allow reasonably good statistics for our conclusions. We find that the incidence of 24 $\mu$m emission is virtually the same in these groups as in the field. This result agrees well with that of Tran et al. (2009) for their luminosity-selected supergroup at $z = 0.37$ but has higher statistical weight because our field sample is significantly larger. This agreement is interesting because Tran et al. (2009) studied supergroups with large velocity dispersions and significant X-ray luminosities, while our groups generally have lower velocity dispersions and no X-ray emission.

This similarity of IR properties appears to hold in detail, both in the forms of the ILFs and as characterized by $L'$. The overall ILFs for groups and field are consistent with being drawn
from the same distribution. Tran et al. (2009) found that $L^*$ for their field sample was $\sim$0.4 dex lower than for their groups. To look for this effect, we used our tLF Schechter function fits to determine $L^*$ for our groups. $L^*$ for our field is marginally larger (again $\sim$0.4 dex) than the groups, though given the error bars on the values of $L^*$, the field and group $L^*$ are comparable. It is possible that the difference between the two studies arises from the different environments—one large group-like structure for Tran et al. (2009) versus our individual, smaller groups. However, given the statistical significance of the two studies, it is plausible that there is no significant overall difference in $L^*$ between the two environments. This emphasizes the lack of any strong dependence of group member properties on the size or mass of the group (Wilman et al. 2005b; this work).

The IR properties of our group and field galaxies appear to be contrary to the shift in the distribution of galaxy morphologies toward early types in groups (McGee et al. 2008; Wilman et al. 2009), which we confirm with a form of CA analysis. In part, this apparent contradiction can be explained by the presence of a number of E/S0 galaxies that are detected at 24 $\mu$m; this IR activity appears to arise from elevated levels of star formation as compared with local E/S0 galaxies (as also found by Tran et al. 2009). However, this behavior has also been seen at similar redshifts in field early-type galaxies (e.g., van der Wel et al. 2007; Pérez-González et al. 2008). Along with a higher population of E/S0 galaxies, the groups also have larger overall numbers of massive, eSps. These galaxies contribute significantly to the numbers of IR-detected group members and to the group LF. Tran et al. (2009) find a similar result for their supergroup: that an excess population (compared with the field) of spirals fills in the dearth of star formation that would otherwise exist because of the larger proportion of early-type galaxies. A minor difference is that the Tran et al. (2009) group sample is rich in relatively low-mass star-forming spirals compared with those in our groups.

An interesting observation is that there are only two galaxies total in our group and field sample that can be classified as ULIRGs ($12 \lesssim \log(L_{\text{TIR}}/(L_\odot)) \lesssim 13$). Le Floc’h et al. (2005) showed that ULIRGs make up only $\sim$10% of the IR population at $z \sim 0.7$, which roughly means, at the redshifts we are studying here, we should expect to see $\sim$4–12 ULIRGs. While the errors on this estimate are almost certainly large enough to encompass our two ULIRGs, it is still odd that our sample lies at the low end of the expected range. If galaxies in groups have higher propensities for mergers or low-velocity encounters, we might expect to see more of these high-$L_{\text{TIR}}$ galaxies in the groups, if not overall. Geach et al. (2009) suggest that such encounters could be fueling the growth of galactic bulges, which explains the larger fraction of Sa through E galaxies in the groups. If we do not see massive amounts of star formation in the groups—or, in this case, neither the groups nor the field—then either a process common to both group and field galaxies is responsible for the bulge formation or star formation from mergers and low-velocity encounters is short enough to not show significant IR emission in individual galaxies.

Because mass has been shown to have significant association with suppressing star formation, we also made a quantitative test of the overall similarity of group and field members of similar mass. The ratio of low-activity star-forming galaxies (i.e., those with SFR $< 2.7 M_\odot$ yr$^{-1}$) to the total number of galaxies with $M_*>10^{10} M_\odot$ is 0.69. We synthesized this result from field galaxies in a Monte Carlo calculation, drawing randomly from a field sample matched in mass. The synthesized distribution is Gaussian and has its maximum probability at a fraction of 0.66, with a range at $\pm 1\sigma$ from 0.62 to 0.70. That is, there is only marginal evidence (1$\sigma$) for a change in incidence of high levels of star formation in galaxies of the same mass in groups versus the field, and any such change is limited to be no more than a 10% effect (at 1$\sigma$).

All of these results are consistent with the hypothesis that the difference between the group and field populations is confined largely to their differing mass functions. For a given mass and morphological type, there is no statistically significant suppression or enhancement of star formation in individual group galaxies in the intermediate stellar mass range of $10^{10}$ to $2 \times 10^{11} M_\odot$. However, groups have begun to build massive galaxies with lower sSFRs as typical for their relatively early types. The shifts toward lower sSFRs and toward higher masses tend to cancel each other, leading to similar infrared tLFs.

We must remind ourselves, however, that we are only probing the brightest star-forming galaxies at these redshifts; galaxies with SFRs below our detection limit could be more affected by the group environment, resulting in a lower fraction of star-forming galaxies in the groups (Peng et al. 2010). Locally, the fraction of IR-active galaxies in the two environments differs by $\sim$30% (more star-forming galaxies in the field) for galaxies with SFRs $\gtrsim 0.1 M_\odot$ yr$^{-1}$, a much lower detection limit than our sample (Bai et al. 2010). Other group studies have found environmental dependence of the fractions of star-forming group and field galaxies at fixed luminosity or stellar mass using different indicators (Wilman et al. 2005a, 2008; Balogh et al. 2007, 2009).

These differences suggest that groups are indeed an intermediate stage between the field and clusters. Our groups contain fractions of E and S0 galaxies at levels comparable to clusters (Wilman et al. 2009), and the mass distribution of group galaxies tends to extend higher than that of field galaxies, as confirmed with a more detailed inspection of the group and field galaxy masses. Despite these differences, the overall IR activity in groups seems to indicate a lack of suppression or enhancement of star formation as compared with the field: the fractions of star-forming galaxies (SFR $> 2.7 M_\odot$ yr$^{-1}$) are comparable in the groups and field, and the tLFs are nearly identical. Individual galaxies of similar mass and morphology appear to have virtually identical infrared properties in the two environments. Thus, the group environment affects the masses and morphologies of galaxies, and their star-forming properties change consistent with these effects. However, any additional changes in star-forming properties are, at best, subtle, at least for SFR $> 2.7 M_\odot$ yr$^{-1}$, indicating that the level of star formation is driven primarily by galaxy mass, itself a function of environment. In other words, star-forming activity in individual galaxies is only indirectly related to the group versus field environment but is linked more strongly to the overall change in galaxy masses and morphologies. The higher $L^*$ for the supergroup of Tran et al. (2009) may indicate an enhancement of star formation that is environmentally dependent, but they find that mass more strongly affects star formation. Apparently, the assumed increased rate of galaxy–galaxy interactions in groups either does not affect the star formation significantly, or strong interaction-driven star formation occurs in environments other than the groups we studied here.

The outskirts of clusters are a probable alternative location for galaxy processing, as shown by the higher fractions of IR-bright galaxies in group and field galaxies than the outskirts of the Coma and A3266 clusters (Bai et al. 2010). Additional
field galaxies (Table 1). Given the density of galaxies in our fields—and how surprising it was to find E/S0 galaxies with possible star formation—we checked each match individually to confirm whether or not the 24 μm emission was coming from the early-type galaxy or if there were a possibility that a close companion was the actual source of the emission. Here, we provide a short description of both the optical and 24 μm sources, as well as HST ACS postage stamps of each galaxy (Figure 12) with error circles matched to the 24 μm emission at 3 arcsec (matching radius) and 6 arcsec (radius of MIPS PSF full width at half maximum (FWHM)).

**PATCH 1447 ID 40969 (Figure 12(a)).** While classified as an “E pec” galaxy (elliptical with a possible interaction from a companion), there are no sources within the 3 arcsec matching radius, and the 24 μm emission is clearly right on top of the elliptical (the emission peaks less than 1 arcsec from the center of the elliptical). The 24 μm emission is definitely coming from the early-type galaxy with no other obvious source.

**PATCH 1447 ID 020364 (Figure 12(b)).** This elliptical galaxy has three small neighbors, though only two are within the 3 arcsec matching radius (the others are slightly farther out). The 24 μm source is closer to the nearest neighbor and close to the edge of the 3 arcsec radius. It is possible that the IR emission is coming from the companion galaxy and not the early type, and so it is not included in our list of IR-active E/S0 galaxies.

**PATCH 1447 ID 041307 (Figure 12(c)).** This galaxy is another peculiar elliptical but with no galaxies within 3 arcsec. The 24 μm source, while faint, is almost directly on top of the elliptical (∼1 arcsec away). It is highly unlikely that the IR emission is coming from another source, so we classify this galaxy as an IR-active early type.

**PATCH 1447 ID 111706 (Figure 12(d)).** Classified as a normal elliptical galaxy, this source has faint 24 μm emission that lies almost on top of the galaxy (∼1 arcsec) with no other obvious galaxies within the match radius. This object has deep X-ray coverage as well, with no detected X-ray source to account for the IR emission. We include this elliptical in our list of star-forming early-type galaxies.

**PATCH 1447 ID 122388 (Figure 12(e)).** Other than being classified as an “E/S0” (somewhere between an elliptical and an S0 galaxy, but more closely resembling an elliptical), this galaxy’s situation is almost identical to the previous one.

**PATCH 1447 ID 150408 (Figure 12(f)).** Here is another regular elliptical galaxy with only one point-source-like neighbor within 3 arcsec. The 24 μm source is well within the match.

5. CONCLUSIONS

We have observed 26 galaxy groups and accompanying field galaxies with deep MIPS photometry and used 24 μm flux densities to estimate the total IR luminosities and SFRs of galaxies in both environments. We find that on an individual basis, group and field galaxies of similar mass and morphology do not differ significantly in terms of their SFRs, and the amount of star formation does not depend on the richness of the groups. However, the groups have systematically lower sSFRs and a higher incidence of massive early-type galaxies, more reminiscent of clusters than the field. We discovered that some of these E and S0 galaxies, as well as a large contingent of massive early spirals, are still forming stars at significant levels.

APPENDIX

Our initial coordinate matching of MIPS 24 μm sources to their optical counterparts resulted in 11 early-type (E or S0) galaxies with possible IR emission: seven group and four field galaxies (Table 1). Given the density of galaxies in our studies of groups and clusters at a variety of redshifts, preferably to lower SFR limits, are needed to further disentangle the effects of these moderately dense environments on the star formation, mass, and morphology of their member galaxies.

### Table 1

| Patcha | ID      | R.A.     | Decl. | z    | L\text{IR} (10^{10} \text{ L}_\odot) | SFR (\text{M}_\odot \text{ yr}^{-1}) | Groupb | Galaxy Type | X-ray Coverage? |
|---------|---------|----------|-------|------|-------------------------------------|-------------------------------------|--------|-------------|-----------------|
| 1447    | 040969  | 222.377813 | 9.511117 | 0.35 | 3.8                                 | 3.7                                  | 23 E pec | N            |                 |
| 1447    | 020364  | 222.431575 | 9.232753 | 0.36 | 11                                  | 12                                   | 25 E    | N            |                 |
| 1447    | 041307  | 222.427158 | 9.536456 | 0.54 | 4.9                                 | 4.8                                  | 39 E pec | N            |                 |
| 1447    | 111706  | 222.483754 | 8.940261 | 0.39 | 0.89                                | 0.78                                 | 32 E    | Y            |                 |
| 1447    | 122388  | 222.355163 | 9.074511 | 0.41 | 0.96                                | 0.85                                 | 0 E/S0  | Y            |                 |
| 1447    | 150408  | 222.184342 | 8.842967 | 0.32 | 1.7                                 | 1.5                                  | 0 E     | N            |                 |
| 1447    | 111547  | 222.470204 | 8.926272 | 0.30 | 1.0                                 | 0.91                                 | 0 E     | Y            |                 |
| 1447    | 120982  | 222.349458 | 8.990908 | 0.37 | 3.0                                 | 2.8                                  | 0 S0 pec | Y            |                 |
| 1447    | 091003  | 222.578538 | 9.010039 | 0.40 | 1.1                                 | 1.0                                  | 32 S0/a | N            |                 |
| 1447    | 091304  | 222.578025 | 9.030156 | 0.37 | 2.4                                 | 2.2                                  | 28 S0   | N            |                 |
| 2148    | 141211  | 327.600550 | −5.681283 | 0.44 | 4.5                                 | 4.3                                  | 138 S0/E | Y            |                 |

Notes.

a Original CNOC2 patch number (Yee et al. 2000).
b Galaxy group to which the object belongs; a 0 value indicates a field galaxy.
and though it is slightly closer to the faint companion, the 24 μm galaxy barely lies within 3 arcsec of the early-type galaxy, listed as IR active from the S0. We conservatively do not include this early type emission is well within the match radius boundary (∼2 arcsec from the elliptical). It is uncertain as to which source the 24 μm emission is coming from, so we removed this galaxy to not include this galaxy as an IR-active source. 

PATCH 1447 ID 111547 (Figure 12(g)). This is a normal elliptical galaxy with two close companions, one of which appears to be a faint irregular fully within the matching radius. The MIPS source appears extended and spans the distance between this closer neighbor and the elliptical. As with the previous galaxy, the uncertainty in the source of the 24 μm emission forced us to not include this galaxy as an IR-active source.

PATCH 1447 ID 120982 (Figure 12(h)). A very faint irregular galaxy barely lies within 3 arcsec of the early-type galaxy, listed as a peculiar S0. The IR source is again between the two galaxies, and though it is slightly closer to the faint companion, the 24 μm emission is well within the match radius boundary (∼2 arcsec from the S0). We conservatively do not include this early type as IR active.

PATCH 1447 ID 091003 (Figure 12(i)). This galaxy is an S0/a, meaning it closely resembles an S0 galaxy but with some Sa qualities. There are no other galaxies within 3 arcsec, and the IR source peaks ∼1 arcsec from the S0/a. We include this object as a star-forming early-type galaxy.

PATCH 1447 ID 091304 (Figure 12(j)). This normal S0 is almost identical to the previous galaxy.

radius, but it is between the nearby object and the elliptical (∼2 arcsec from the elliptical). It is uncertain as to which source the 24 μm emission is coming from, so we removed this galaxy for matching the optical coordinates with 24 μm sources. The outer annulus shows the FWHM of the MIPS PSF. The ID and patch number of the matched galaxies are as follows: (a) 1447 040969, (b) 1447 020364, (c) 1447 041307, (d) 1447 111706, (e) 1447 122388, (f) 1447 150408, (g) 1447 111547, (h) 1447 120982, (i) 1447 091003, (j) 1447 091304, and (k) 2148 141211. (A color version of this figure is available in the online journal.)

Figure 12. HST ACS images of the 11 E/S0 galaxies matched with 24 μm sources. The inner annulus has a radius of 3 arcsec, which is the length we used for matching the optical coordinates with 24 μm sources. The outer annulus shows the FWHM of the MIPS PSF. The ID and patch number of the matched galaxies are as follows: (a) 1447 040969, (b) 1447 020364, (c) 1447 041307, (d) 1447 111706, (e) 1447 122388, (f) 1447 150408, (g) 1447 111547, (h) 1447 120982, (i) 1447 091003, (j) 1447 091304, and (k) 2148 141211. (A color version of this figure is available in the online journal.)

Figure 13. Optical and IR SEDs (rest frame) for all six star-forming E/S0 galaxies, identified by their GEEC ID and fit by different segments of the Rieke et al. (2009) average star-forming galaxy templates. Each galaxy was matched to the average template with the closest L_{TIR} and fit to the 24 μm data point (red spectra). The orange spectra are best-fit (χ^2) average star-forming templates for the optical/near-IR photometry; while these fits are not very accurate, they are sufficient for our purposes. Except for 40969 and 41307, all galaxies have enough photometric points to indicate the presence of a stellar bump and mid-IR dust emission similar to normal star-forming galaxies. (A color version of this figure is available in the online journal.)

PATCH 1447 ID 141211 (Figure 12(k)). As with the previous two galaxies, this S0/E (S0 galaxy somewhat similar to an elliptical) has no other companions within 3 arcsec (though there are two faint galaxies between 3.5 and 5 arcsec away). The 24 μm emission is slightly offset from the galaxy (∼1 arcsec) but within the match radius. A very faint galaxy lies ∼1.5 arcsec from the 24 μm position. While it seems likely that the IR emission is coming from the S0 galaxy, we took a conservative stance and do not classify this galaxy as IR active.

In Figure 13, we plot rest-frame optical and IR SEDs for the six E/S0 galaxies that have confirmed IR emission. The stellar outputs of these galaxies may be dominated by a relatively old population. Therefore, we fit Rieke et al. (2009) average star-forming galaxy templates to the SEDs in two distinct segments. First, we found the average template with the closest L_{TIR} to each galaxy and fit the 24 μm data point to the template (red spectrum). For the normal stellar emission, we used optical and near-IR photometry to find the best-fit (χ^2) average star-forming template (orange spectrum). Except for the first two galaxies, we see a clear stellar bump from normal stars and then increasing luminosity of the mid-IR dust emission beyond 7 μm, indicative of a normal star-forming galaxy and not an AGN. In all cases, the SED is consistent with the expectation for star formation. There are two cases where (1) there are IRAC data and (2) a detection of the aromatic emission at 8 μm is predicted from the combination of IRAC bands 1–3 and the MIPS 24 μm flux density. The expected 8 μm excess is seen for both galaxies.

REFERENCES

Abraham, R. G., Valdes, F., Yee, H. K. C., & van den Bergh, S. 1994, ApJ, 432, 75

Abraham, R. G., van den Bergh, S., Glazebrook, K., Ellis, R. S., Santiago, B. X., Surma, P., & Griffiths, R. E. 1996, ApJS, 107, 1
