THE SUPPRESSION OF STAR FORMATION AND THE EFFECT OF THE GALAXY ENVIRONMENT IN LOW-REDSHIFT GALAXY GROUPS

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ABSTRACT

Understanding the interaction between galaxies and their surroundings is central to building a coherent picture of galaxy evolution. Here we use Galaxy Evolution Explorer imaging of a statistically representative sample of 23 galaxy groups at \( z \approx 0.06 \) to explore how local and global group environments affect the UV properties and dust-corrected star formation rates (SFRs) of their member galaxies. The data provide SFRs out to beyond \( 2R_{200} \) in all groups, down to a completeness limit and limiting galaxy stellar mass of 0.06 \( M_\odot \) yr\(^{-1} \) and \( 1 \times 10^8 \) \( M_\odot \) respectively. At fixed galaxy stellar mass, we find that the fraction of star-forming group members is suppressed relative to the field out to an average radius of \( R \approx 1.5 \) Mpc. For the first time, we also report a similar suppression of the specific SFR within such galaxies, on average by 40% relative to the field, thus directly revealing the impact of the group environment in quenching star formation within infalling galaxies. At fixed galaxy density and stellar mass, this suppression is stronger in more massive groups, implying that both local and global group environments play a role in quenching. The results favor an average quenching timescale of \( \gtrsim 2 \) Gyr and strongly suggest that a combination of tidal interactions and starvation is responsible. Despite their past and ongoing quenching, galaxy groups with more than four members still account for at least \( \sim 25\% \) of the total UV output in the nearby universe.

Keywords: galaxies: evolution – galaxies: groups: general – galaxies: star formation – ultraviolet: galaxies

Online-only material: color figures

1. INTRODUCTION

Galaxies may evolve from star-forming (SF) late types to passive early types either via internal, secular processes or through mechanisms induced by their environment. Disentangling these two pathways and understanding the nature and impact of various environmental processes on galaxy evolution is a major goal of contemporary astrophysics. While the overall star formation density of the universe has declined significantly since a redshift of \( z \approx 2 \) (Madau et al. 1996; Hopkins & Beacom 2006), this evolution appears to be accelerated in dense environments, with groups and clusters of galaxies containing a lower fraction of SF galaxies at fixed stellar mass and redshift than the general field (e.g., Kauffmann et al. 2004; Mcgee et al. 2011).

Recent work has demonstrated that the effect of secular evolution in quenching star formation, primarily driven by galaxy stellar mass, can be separated from that of the galaxy environment (Peng et al. 2010). The former effect dominates at high galaxy masses, whereas environmental quenching of star formation becomes increasingly important at lower masses. Possible mechanisms for a more rapid quenching of low-mass galaxies in dense environments include tidal interactions, harassment, ram pressure stripping, starvation, and major and minor mergers.

Groups of galaxies are particularly interesting in this respect. Containing around half of all galaxies and most of the stellar mass in the local universe (Eke et al. 2004, 2005), they represent a key environment in the hierarchical build-up of cosmic structure. The galaxy population within groups has evolved significantly since \( z \approx 0.5 \), with the fraction of emission-line galaxies having declined substantially (Wilman et al. 2005). Interestingly, however, the emerging picture is the one in which star formation in SF galaxies of a given stellar mass is similar in groups and the field, whereas the fraction of such galaxies is not (e.g., Balogh et al. 2004; Baldry et al. 2006; Iovino et al. 2010). For example, Balogh et al. (2004) used inferred Hz equivalent widths of galaxies within a large sample of low-redshift groups in the Sloan Digital Sky Survey (SDSS) and 2dF Galaxy Redshift Survey (2dFGRS) catalogs to show that the fraction of SF galaxies depends systematically on local density, but the actual star formation rate (SFR) in such galaxies does not. This has recently been shown to apply also at intermediate redshifts, \( z \sim 0.4 \), and at fixed stellar mass (Mcgee et al. 2011), and the result has further been extended to galaxies in both nearby (Haines et al. 2011) and distant (\( z \sim 1 \); Muzzin et al. 2012) clusters and superclusters.

This has been interpreted as evidence that the truncation of star formation is accomplished on short timescales, rapidly enough to leave the average star formation properties of SF galaxies largely unaffected. This would be true even in groups of fairly low mass, and support for this comes from recent studies based on UV SFRs in Hickson Compact Groups (HCGs) which are generally relatively sparse systems. Such work has revealed a pronounced deficit of galaxies with moderate specific (i.e., stellar-mass-normalized) SFRs (Tzanavaris et al. 2010; Walker et al. 2012), consistent with a rapid, environment-driven transition from (perhaps temporarily enhanced) star formation to quiescence. Although the dominant responsible mechanism(s) have yet to be unambiguously identified, it is

* This paper includes data gathered with the 6.5 m Magellan Telescopes located at Las Campanas Observatory, Chile.
clear that galaxy–galaxy interactions could play a prominent role both in compact and more typical groups, given the relatively low velocity dispersions characteristic of these environments.

Recognizing that a detailed multi-wavelength characterization of the coupling between global group properties and those of the member galaxies themselves could offer important new insights, we initiated the XI Groups Survey, a study of a statistically representative sample of 25 redshift-selected groups at \( z \approx 0.06 \) (Rasmussen et al. 2006b). In this framework, we have previously presented SFRs from Spitzer/MIPS 24 \( \mu \)m data for a subset of nine groups (Bai et al. 2010). Results revealed SF galaxy fractions that bridge those of the field and massive clusters, being everywhere higher than those in cluster outskirts but lower than in the field by \( \sim 30\% \) on average. The fractions showed no systematic dependence on global group properties such as velocity dispersion or total stellar mass. In addition, and in line with the above previous studies, specific SFRs (sSFRs) were generally found to be similar to those in the field.

One limitation of our Spitzer study was the narrowness of the rectangular region (20', equivalent to \( \sim 0.7 \) Mpc radius at the sample redshift) covered by our MIPS observations. To fully understand the suppression of star formation in groups requires establishing the SF properties of group members out to larger radii and including galaxies that are encountering the group environment for the first time. For example, simulations (Kawata & Mulchaey 2008) and isolated observations (Rasmussen et al. 2006a) suggest that gaseous stripping and starvation can suppress star formation in disk galaxies on their first passage through even low-mass groups. In more massive clusters, SFRs appear suppressed out to \( R \sim 2R_{200} \) (Balogh et al. 1998; here \( R_{200} \) is the radius enclosing a mean overdensity of 200 relative to the critical density). Recent studies have extended this conclusion to even larger radii (Chung et al. 2011), revealing a suppression in the fraction of SF galaxies out to \( \sim 7 \) Mpc from cluster cores (Lu et al. 2012). However, other works have also shown that star formation can be locally enhanced well outside the cluster virial radius for galaxies within the filaments feeding these structures (Porter & Raychaudhury 2007; Fadda et al. 2008; Porter et al. 2008; Pereira et al. 2010), with galaxy–galaxy interactions among infalling galaxies providing a possible explanation. Testing the general validity of these results for low-mass groups requires full coverage of the group environment out to the field and infall regions.

Here we extend our previous Spitzer study by presenting Galaxy Evolution Explorer (GALEX) data for most of the full XI sample. Apart from providing improved statistics due to the increased sample size, the GALEX field of view of \( R = 36' \) also allows coverage of each group field out to \( R \sim 2.5 \) Mpc, corresponding to at least \( 2R_{200} \) for these systems. This continuous coverage of all regions from the general “field” through the infall regions to the dense group cores enables a complete census of the SF properties of group galaxies, including those only now encountering the group environment.

We assume \( H_0 = 72 \) \( \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1} \), \( \Omega_m = 0.27 \), and \( \Omega_{\Lambda} = 0.73 \). At the sample median redshift of \( z = 0.061 \), 1' corresponds to 69 kpc and the total GALEX field to \( \sim 5.0 \) Mpc diameter. All uncertainties are quoted at the 1\sigma level.

2. OBSERVATIONS AND ANALYSIS

2.1. Sample and Optical Observations

Details of the XI sample selection are given in Rasmussen et al. (2006b), but we repeat here that the sample comprises 25 groups selected from systems identified by Merchán & Zandivarez (2002) in the 100 K data release of the 2dFGRS (Colless et al. 2001). Groups with at least five members and having velocity dispersion \( \sigma < 500 \) \( \text{km} \, \text{s}^{-1} \) were selected randomly within the redshift range \( z = 0.060-0.062 \) to span the full parameter space in \( \sigma \), galaxy richness, and estimated virial radii. Barring any inherent biases in the friends-of-friends algorithm used to build the parent group catalog, the sample is intended to be unbiased and truly representative of the low-redshift group population.

An extensive imaging and spectroscopic campaign with the IMACS spectrograph at the 6.5 m Baade/Magellan telescope at Las Campanas has more than doubled the number of spectroscopically identified group members compared to the original Merchán & Zandivarez (2002) catalog. This has enabled highly reliable estimates of velocity dispersion and luminosity centroid for each group. In the present work, we adopt as group centers the location of the brightest group galaxy within a projected distance of 0.5 Mpc of the \( R \)-band luminosity-weighted center, and with velocity within \( 2\sigma \) of the group mean. A forthcoming paper (L. Bai et al. 2012, in preparation) will provide the full details and results of our optical spectroscopy and Spitzer 24 \( \mu \)m imaging of the full XI sample, along with the individual galaxy redshifts, stellar mass estimates, UV photometric measurements, and SFR estimates used in the present work.

Following the procedure in Bai et al. (2010), we have here complemented our optical spectroscopy within the \( R \approx 15' \) IMACS field of view with redshift measurements from existing catalogs out to \( R = 35' \) from the center of each group. These redshifts come mainly from the 2dFGRS (see Bai et al. 2010 for further details). Galaxies were included in the present study if having recession velocities within \( 3\sigma \) of the group mean, as determined from the galaxies within the central \( R = 1 \) Mpc. Some fraction of these objects are likely to represent a population of infalling galaxies that are only now encountering the group environment, and some may represent true “field” galaxies. This allows us to probe the impact of the group environment on the UV properties of galaxies out to well beyond the group virial radii. However, we emphasize that this auxiliary sample is more heterogeneous than the one covered by our IMACS spectroscopy and that some of these galaxies should be considered candidate rather than bona fide group members. We will comment on the potential impact of this whenever relevant.

A subset of the group members has five-band photometry from the SDSS. For these galaxies, we used the kcorrect package (Blanton & Roweis 2007) to derive a relation between their \( R \)-band stellar mass-to-light ratio and their \( B-R \) color. This relation was then used to estimate stellar masses \( M_* \) for the full group sample, with a typical uncertainty for individual galaxies of \( \sim 45\% \) (see Bell et al. 2003). For 17 of the 833 galaxies discussed in this paper (2%), only \( R \) magnitudes are available, and \( M_* \) for these was determined in a similar fashion from their \( R \) magnitudes alone.

2.2. GALEX Observations and Photometry

Of the 25 groups within the XI sample, 22 were imaged by GALEX in both bands (NUV: 1770–2830 Å; FUV: 1340–1790 Å) as part of GI Cycle 4 (PI: Mulchaey). The median exposure in both bands was 1600 s. One further group (MZ 5383) was covered in the GALEX Medium Imaging Survey to comparable depth. The final two XI groups, MZ 3849 and MZ 9994, suffer from bright stars within the field above the
and 601 (72%) are detected in both UV bands. The number of group members within the 24′ aperture varies across groups, as detailed in Table 1. For source identification, the SExtractor-generated source catalog was cross-correlated with a list of spectroscopically identified group members, flagged for each member the nearest UV source within a maximum separation of 5″ as a match. This separation roughly corresponds to the full width at half-maximum of the NUV point-spread function. Table 1 lists for each group the number of spectroscopic (including candidate) members \( N_{\text{gal}} \) within the GALEX field, and the subset of those detected in both UV bands and at 24 μm. Out of a total of 833 group members within the GALEX fields, 721 (622) are detected in NUV (FUV), and 601 (72%) are detected in both UV bands.

We focus here exclusively on the integrated UV properties of the group galaxies, since the majority of the group members are only slightly, if at all, resolved by GALEX. We adopted NUV and FUV total magnitudes measured within elliptical apertures scaled to 2.5 times the Kron diameter, as provided by the GALEX pipeline on the basis of sky-subtracted and response-corrected images. For resolved sources, these apertures are generally comparable to the \( D_{25} \) aperture obtained from B-band photometry (Donas et al. 2007).

All magnitudes were corrected for Galactic extinction using the reddening maps of Schlegel et al. (1998) and the results of Wyder et al. (2005). These corrections range from 0.1–0.5 mag, with a median extinction of 0.15 mag in both bands. Magnitudes were also \( k \)-corrected, by using the GALEX stellar evolutionary synthesis code (Kotulla et al. 2009) to construct a grid of galaxy spectral models that cover the region occupied by the group members. The models assumed a Salpeter initial mass function (IMF) along with various star formation histories and levels of intrinsic extinction. For each observed group galaxy, predicted \( k \)-corrections from the code associated with the nearest match in color space were then applied. With the exception of very red early-types and strongly star-bursting spirals, the corrections are generally ≤0.1 mag in both bands for all group members. As mentioned, all UV photometry for individual galaxies will be presented in a forthcoming paper (L. Bai et al. 2012, in preparation).

With most of our group members remaining unresolved, we cannot directly estimate the contribution of any active galactic nucleus (AGN) activity to the UV flux. However, the fraction of AGN identifiable on the basis of their optical emission lines

| Group     | R.A.   | Decl.  | \( t_{\text{exp}} \) | Ext. (mag) | \( z \) | \( \sigma \) (km s\(^{-1}\)) | \( M_{\text{tot}} \) (log \( M_\odot \)) | \( N \) | \( N_{\text{gal}} \) | \( N_{\text{UV}} \) | \( N_{24 \mu m} \) |
|-----------|--------|--------|----------------------|------------|------|-----------------|--------------------------|-----|-------------|-------------|-------------|
| MZ 770    | 22°18′03″36″ | −28°22′58″8′ | 1245 | 0.14 | 0.0606 | 215 | 11.21 | 15 | 12 | 9 | 2 |
| MZ 1766   | 00°38′31″19″ | −27°11′16″8′ | 1658 | 0.11 | 0.0611 | 222 | 11.62 | 15 | 40 | 30 | 10 |
| MZ 3067   | 22°16′16″32″ | −25°42′25″2′ | 1333 | 0.18 | 0.0602 | 160 | 11.49 | 16 | 32 | 29 | 8 |
| MZ 3182   | 22°19′17″28″ | −27°01′22″8′ | 1563 | 0.15 | 0.0611 | 258 | 11.14 | 8 | 22 | 18 | 5 |
| MZ 3541   | 10°03′41″04″ | −04°09′50″4′ | 1586 | 0.30 | 0.0627 | 121 | 11.30 | 11 | 21 | 16 | 10 |
| MZ 3698   | 09°59′27″36″ | −05°43′58″8′ | 1600 | 0.21 | 0.0609 | 215 | 11.53 | 14 | 21 | 12 | 7 |
| MZ 4001   | 10°16′23″28″ | −03°15′18″0′ | 1593 | 0.27 | 0.0593 | 325 | 11.73 | 36 | 60 | 45 | 15 |
| MZ 4548   | 10°53′52″38″ | −05°39′42″0′ | 1565 | 0.25 | 0.0625 | 157 | 10.86 | 12 | 24 | 19 | 7 |
| MZ 4577   | 11°33′05″04″ | −04°00′46″8′ | 2609 | 0.44 | 0.0621 | 232 | 11.35 | 20 | 44 | 31 | 9 |
| MZ 4592   | 11°30′51″12″ | −03°47′27″6′ | 1656 | 0.51 | 0.0616 | 206 | 11.50 | 18 | 37 | 24 | 10 |
| MZ 4881   | 11°39′48″00″ | −03°30′28″8′ | 2885 | 0.19 | 0.0612 | 351 | 11.65 | 34 | 52 | 42 | 21 |
| MZ 4940   | 11°36′04″80″ | −03°39′57″6′ | 3171 | 0.37 | 0.0620 | 64 | 11.12 | 8 | 13 | 11 | 5 |
| MZ 5293   | 12°16′19″92″ | −03°21′00″0′ | 1666 | 0.33 | 0.0620 | 104 | 11.32 | 9 | 10 | 5 | 4 |
| MZ 5383   | 12°35′47″52″ | −03°41′24″0′ | 1186 | 0.30 | 0.0595 | 190 | 11.39 | 17 | 31 | 24 | 3 |
| MZ 5388   | 12°34′04″56″ | −03°22′22″8′ | 1670 | 0.33 | 0.0598 | 144 | 11.33 | 14 | 19 | 16 | 8 |
| MZ 8816   | 00°05′58″32″ | −27°52′26″4′ | 1564 | 0.14 | 0.0608 | 291 | 11.48 | 25 | 68 | 34 | 16 |
| MZ 9014   | 00°37′48″00″ | −27°30′28″8′ | 1750 | 0.11 | 0.0608 | 283 | 11.49 | 24 | 46 | 40 | 6 |
| MZ 9069   | 00°28′25″20″ | −27°28′58″8′ | 1584 | 0.13 | 0.0615 | 361 | 11.43 | 29 | 64 | 45 | 14 |
| MZ 9137   | 00°18′54″64″ | −56°54′57″6′ | 1596 | 0.19 | 0.0598 | 329 | 11.15 | 13 | 22 | 17 | 6 |
| MZ 9307   | 00°40′48″72″ | −27°27′07″2′ | 1704 | 0.10 | 0.0598 | 384 | 11.02 | 20 | 41 | 34 | 2 |
| MZ 10167  | 01°51′12″48″ | −27°44′09″6′ | 1599 | 0.14 | 0.0606 | 201 | 11.30 | 20 | 29 | 27 | 11 |
| MZ 10300  | 02°24′27″12″ | −28°19′19″2′ | 1624 | 0.15 | 0.0618 | 271 | 11.44 | 29 | 50 | 29 | 8 |
| MZ 10451  | 02°29′30″48″ | −29°37′44″4′ | 1607 | 0.14 | 0.0610 | 455 | 11.64 | 40 | 75 | 44 | 18 |

Notes. Columns 2 and 3: GALEX pointing coordinates. Column 4: effective FUV exposure time. Column 5: mean Galactic FUV extinction across the GALEX field. Columns 6–8: mean group redshift, velocity dispersion, and total stellar mass of the group members within \( R = 1 \) Mpc of the group center. Column 9: number of group members used to compute \( z \), \( \sigma \), and \( M_{\text{tot}} \). Column 10: total number of spectroscopically identified group member candidates within the GALEX field. Column 11: number of group members within the GALEX field detected in both NUV and FUV bands. Column 12: number of group members within the GALEX field detected at 24 μm.
or their X-ray properties is small for the X-ray sample, at the few percent level (Shen et al. 2007; Bai et al. 2010), so AGN contamination in the UV is generally unlikely to be important. In addition, the dependence of the AGN fraction on global environment is generally inferred to be weak (Arnold et al. 2009), so we do not expect environmental variations in AGN activity to significantly impact our results.

The approximate 100% completeness limit for our GALEX observations in either band can be estimated from the apparent magnitude histograms of all sources detected in the field of MZ 4592, the group with the highest Galactic extinction, MZ 4592. The dotted vertical line outlines the approximate 100% completeness limit adopted in this paper. Legends give the total number of NUV and FUV sources detected within each field.

Figure 1. Histograms of observed NUV and FUV magnitudes of all sources detected above 3σ significance in our shortest exposure, MZ 770, and the one with highest Galactic extinction, MZ 4592. The dotted vertical line outlines the approximate 100% completeness limit adopted in this paper. Legends give the total number of NUV and FUV sources detected within each field. (A color version of this figure is available in the online journal.)

2.3. Dust-corrected UV Star Formation Rates

The UV light from SF galaxies is dominated by emission from intermediate-mass stars younger than \(\approx 10^8\) yr (Kennicutt 1998). Assuming that the SFR has remained roughly constant over this timescale, it should be proportional to the intrinsic galaxy UV luminosity \(L_{\text{UV}}\). Estimates of UV SFRs are model dependent, however, in part because they need to be corrected for attenuation by dust (potentially by an order of magnitude), and in part because the conversion of the dust-corrected \(L_{\text{UV}}\) to an SFR depends on the assumed stellar metallicity and IMF, along with the geometry of the distribution of dust and stars.

To estimate these dust corrections, we utilize our existing 24 \(\mu\)m photometry wherever possible and follow the approach of Buat et al. (2005) to derive the FUV attenuation \(A_{\text{FUV}}\) as a function of FUV and total infrared luminosity \(L_{\text{TIR}}\) (see Bai et al. 2010), using

\[
A_{\text{FUV}} = (-0.0333)\gamma^3 + 0.3522\gamma^2 + 1.1960\gamma + 0.4967,
\]

where \(\gamma = \log(L_{\text{TIR}}/(\nu L_\nu))\), \(\nu = 1.96 \times 10^{15}\) Hz is the effective frequency of the GALEX FUV band, and \(L_\nu\) is the measured specific FUV luminosity (in erg s\(^{-1}\) Hz\(^{-1}\)). Dust-corrected SFRs were then obtained as (Salim et al. 2007)

\[
\text{SFR}_{\text{FUV}} (M_\odot \text{yr}^{-1}) = 1.08 \times 10^{-28}\; L_{\text{FUV}},
\]

where \(L_{\text{FUV}}\) is the dust-corrected specific FUV luminosity. Equation (2) is valid for a Salpeter IMF and a mean stellar metallicity of 0.8 \(Z_\odot\).

For the galaxies without a Spitzer detection, FUV magnitudes were first corrected according to Equation (6) in Salim et al. (2007), based on UV magnitudes of normal (NUV–R < 4) SF galaxies:

\[
A_{\text{FUV}} = \begin{cases} 2.99 C_{\text{UV}} + 0.27, & C_{\text{UV}} < 0.90 \\ 2.96, & C_{\text{UV}} \geq 0.90, \end{cases}
\]

where \(C_{\text{UV}} = (\text{FUV–NUV})\) is the rest-frame UV color. The associated dust-corrected SFRs were then compared to those derived on the basis of Equation (1) for all galaxies detected at both NUV, FUV, and 24 \(\mu\)m. This comparison is shown in Figure 2, as a function of the SFR from FUV + IR data (i.e., Equations (1) and (2)) and of galaxy stellar mass. Using UV data alone on average tends to overestimate the SFR relative to the result when combining UV and IR data, and this is more prominent for galaxies with low SFR and high \(M_*\) (see also, e.g., Iglesias-Páramo et al. 2006; Cortese et al. 2008a).

To bring our UV-only estimates into better agreement with those obtained from the combined use of UV and 24 \(\mu\)m data, we performed a linear fit to the full data in Figure 2(b), implying

\[
\log \left(\frac{\text{SFR}_{\text{FUV}}}{\text{SFR}_{\text{FUV+IR}}}\right) = 0.084\log (M_*/M_\odot) - 0.64,
\]

with a mean absolute deviation of 0.18 dex (which is comparable to the typical uncertainty on \(M_*\)). This result, shown as a solid line in the figure, is consistent with that obtained for the blue galaxies only (NUV–R < 4, for which Equation (3) is valid). We use it to correct the inferred SFR for galaxies without a Spitzer detection at a given \(M_*\). As will be discussed in Section 3.3, the resulting SFRs are, on average, in very good agreement with those obtained in other similar studies. For our adopted UV completeness limit and a minimum Galactic extinction of 0.1 mag (see Table 1), Equation (2) would imply that we are complete to SFR\(_{\text{FUV}} < 0.06\; M_\odot \text{yr}^{-1}\) in all groups before correction for dust.
2.4. Quantifying Galaxy Environment

The inferred UV and star formation properties of the group members are here presented with a focus on their dependence on galaxy environment, using total group stellar mass and/or velocity dispersion as main indicators of global group environment. One further indicator, discussed below, is obtained by dividing the groups into ones containing UV–optical red and blue central galaxies, respectively.

Local galaxy environment is quantified by projected distance \( R \) to the adopted group center, optionally normalized by \( R_{200} \). The latter values were estimated for each group from the radial velocity dispersion and mean redshift using

\[
R_{200} = 1.73\sigma [(\Omega_\Lambda + \Omega_m)(1 + z)^3]^{-1/2} h_{100}^{-1} \text{kpc}
\]

\((5)\)

\(\text{(Finn et al. 2004). Results range from } R_{200} \approx 150–1200 \text{kpc (median of 520 kpc), implying that all groups are covered by GALEX to at least } 2R_{200}.\)

Another commonly used indicator of local environment is the galaxy surface density \( \Sigma_5 = 6/(\pi R_5^2) \), where \( R_5 \) is the projected distance of each galaxy to its fifth nearest neighbor. This can be reliably used across different systems, provided these are globally broadly similar. However, our groups span a wide range in richness and estimated \( R_{200} \), so at fixed three-dimensional galaxy density \( \rho_{\text{gal}} \), projection effects would act to boost \( \Sigma_5 \) progressively more in the larger systems. To compensate for this, we employ instead an estimate of \( \rho_{\text{gal}} \), derived by normalizing \( \Sigma_5 \) by a characteristic radius \( R' \) for each group. Noting that self-similarity would require \( R' \propto \sigma \propto R_{200} \), we simply take \( \rho_{\text{gal}} = \Sigma_5 / R_{200} \). All results reported here are qualitatively similar though if plotted against \( \Sigma_5 \) instead of \( \rho_{\text{gal}} \).

One further issue is our lower spectroscopic completeness outside the \( R \approx 15' \approx 1 \text{ Mpc} \) IMACS field of view, which could act to systematically bias \( \Sigma_5 \) low at large radii. However, we find no evidence for a break around \( R \approx 15' \) in the distribution of \( \Sigma_5 \) versus \( R \) for all group members. Furthermore, the distributions of \( M_R \) for the spectroscopically identified members within and outside the IMACS field are broadly similar down to at least \( M_R \approx -19.0 \), as shown in Figure 3. We find that all our results are quantitatively similar, and all conclusions unaffected, if computing \( \Sigma_5 \) by only including galaxies brighter than this magnitude. Hence, to fully exploit our extensive IMACS spectroscopy, which extends beyond \( R_{200} \) for all groups and to \( 2R_{200} \) for \( \approx 75\% \) of them, we compute \( \Sigma_5 \) and \( \rho_{\text{gal}} \) using all available members.

3. RESULTS

3.1. Galaxy Colors

The UV–optical color, specifically NUV–R, is a useful diagnostic of a galaxy’s recent level of star formation (Salim et al. 2007). A UV–optical color–magnitude diagram for all groups is presented\(^6\) in Figure 4, with each data point color-coded according to its FUV–NUV color. The galaxy sample is seen to split into a dominant population of SF blue-cloud members joined by a smaller number of predominantly optically bright red galaxies. Also shown is the region below the NUV sensitivity limit of our data; this assumes a typical NUV \( 3\sigma \) limiting sensitivity of \( m_{AB} \approx 24.0 \) after correction for Galactic extinction (see Figure 1). This limit prevents the UV detection of optically faint, passive galaxies, so Figure 4 alone may not provide a full picture of the extent of the passive population in these groups. Incompleteness of the UV data will generally be taken into account in the analysis which follows.

An orthogonal regression fit to the NUV–R color as a function of specific SFR (sSFR = SFR/M\(_{\ast}\)) shows that a value of NUV–R < 4 corresponds to sSFR/M\(_{\ast}\) > 10\(^{-10.5}\) yr\(^{-1}\). As will be shown in Section 3.3, considering galaxies above this sSFR cleanly isolates the SF population that dominates these groups. In the following, we will therefore use NUV–R < 4 to separate “SF” galaxies from “passive” ones, noting that this is also the limit to which Equation (3) remains valid. Using this color cut, Figure 4 confirms that SF galaxies are generally relatively FUV bright, as anticipated from Equation (2). In contrast, a large fraction of the passive red galaxies have red FUV–NUV colors, with almost half (43% ± 5%) of them remaining undetected in the FUV.

\(^6\) As is customary, NUV magnitudes have here been corrected for Galactic extinction but not for any intrinsic reddening.
Despite this, we note that bright, central early-type galaxies in massive galaxy clusters can display blue colors and excess UV light beyond that expected from old stars, indicating ongoing star formation (Mahajan & Raychaudhury 2009; Donahue et al. 2010; Hicks et al. 2010). This could potentially be induced by cooling of the intracluster medium onto the massive galaxy at the center of the cluster potential. As such, the color of the central group galaxy might provide another indicator of the global nature of the host environment. To examine this, Figure 5 shows the distribution of NUV–R colors for the 22 central galaxies covered by GALEX, illustrating that the majority (16) are clearly “passive,” NUV–R \( \gtrsim 5 \), and drawn from the red-sequence population within the groups. Visual inspection of our IMACS R-band images, taken in sub-arcsec seeing, confirms that these 16 are all early-type galaxies.

However, a minority of the central galaxies have bluer colors, and all but the reddest one of these are late-type galaxies. These could potentially represent chance projections of blue galaxies situated at large radii, rather than galaxies physically associated with the group cores. They all have \( M_R < -21.0 \) and are situated <0.4 Mpc from the group luminosity centroid. Based on the projected density of equally bright, blue galaxies at larger radii, \( R = 1–2 \) Mpc, we would expect a total of only 0.9 ± 0.2 such galaxies to be projected onto this central region of the relevant groups. Thus, most of these six blue centrals are likely to be physically situated in the group core. On average, they have lower stellar masses than do the red, passive ones, and they also reside further from the group luminosity centroid and in groups of lower total stellar mass (\( (\log (M_* / M_\odot)) = 11.28 \pm 0.09 \)) versus 11.44 ± 0.07 within \( R = 1 \) Mpc), velocity dispersion (\( (\sigma) = 161 \pm 20 \) versus 282 ± 28 km s\(^{-1}\)), and richness (\( (N_{gal}) = 26 \pm 5 \) versus 42 ± 4) than do red central galaxies. This suggests that our blue, late-type centrals reside in group halos that are relatively less massive and dynamically younger, consistent with the finding that the fraction of central group galaxies that are ellipticals is a strong function of group halo mass (Wilman & Erwin 2012). Hence, these blue centrals likely represent ordinary bright SF galaxies, rather than objects with recent (dust-obscured) star formation fueled by cooling of intragroup gas.

Figure 5. Histograms of NUV–R colors for the central group galaxies (filled) and for all galaxies (dotted). Legends give the average \( M_* , \rho_{gal} \), and projected distance \( R_{cen} \) from the group luminosity centroid, for the two classes of central galaxies.

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

3.2. Star-forming Galaxy Fractions

Given Equation (2), the fraction of group members detected in the FUV is equivalent to the fraction of galaxies forming stars above a certain rate. To explore how this quantity depends on galaxy properties and environment, we first apply our cut at \( m_{AB} < 22.0 \) in the FUV (i.e., \( SFR \gtrsim 0.05\ M_\odot\ yr^{-1} \)) before dust correction) to homogenize UV completeness across the sample. The resulting sample was also split at its median stellar mass of \( M_* = 10^{9.75}\ M_\odot \), to elucidate any dependence on galaxy mass. Figure 6 shows the resulting mean FUV fractions as a function of local galaxy environment. The results reveal a clear rise toward group outskirts, out to the largest radii and lowest galaxy densities probed. This trend is robust in both galaxy environments at these radii, we find average SF fractions

Figure 6. Fraction of FUV-detected group members above our UV completeness limit as a function of (a) projected radius from the group center, (b) radius normalized by \( R_{200} \), (c) local galaxy density, and (d) galaxy stellar mass. In panels (a)–(c), squares and triangles show results for the low- and high-mass half of the sample, respectively. Error bars represent Poisson errors on each bin.

(A color version of this figure is available in the online journal.)
above the UV completeness limit of 43% ± 3% in groups and 66% ± 6% in the field. This implies a decrease in mean SF fraction by 35% ± 8% in groups relative to the field, in agreement with the 30% decline found from our Spitzer data of nine of the groups (Bai et al. 2010).

These trends could potentially just reflect an underlying variation in average galaxy stellar mass, with high-density group cores being dominated by more massive, red, and generally UV-faint galaxies. However, any residual mass dependence from bin to bin in panels (a)–(c) is limited to a non-systematic variation in mean $M_*$ with environment of <0.2 dex. Furthermore, the decline in FUV fraction with $M_*$ is weaker than that with environmental parameters, as shown in Figure 6(d), even when including the UV detections below our completeness limit. The implication is that the observed trends are indeed environment driven rather than reflecting environmental variations in mean $M_*$.

To explore any dependence on global group environment, Figure 7 displays the total FUV fractions within $R_{200}$ as a function of total group stellar mass $M_*$, in four stellar mass bins containing a similar number of groups. The data show a systematic decline in average SF galaxy fraction with group stellar mass and velocity dispersion, from ~70% in the lowest-mass bin to ~30% for the most massive systems. Although subject to larger errors, the overall trend persists if subdividing the galaxy population into a low- and high-mass half (see the figure inset), and so is not driven by systematic differences in average galaxy $M_*$ with total group stellar mass. Hence, even across the range of relatively low host halo masses considered here, the overall star formation activity is systematically modulated by global environment.

### 3.3. Star Formation Rates

For comparing dust-corrected SFRs of the 601 galaxies detected in both UV bands, we bring all objects on an equal footing by presenting their sSFR in Figure 8. Above our approximate completeness limit, there is a clear decline in the average sSFR with $M_*$, across three orders of magnitude in stellar mass, and a corresponding increase in the UV–optical color. The dashed line in the figure shows the value of $sSFR = 10^{-10.5} \text{yr}^{-1}$ that corresponds to the adopted distinction between passive and SF galaxies at NUV–R = 4, as suggested by a regression fit between the two quantities; this is a reliable and robust criterion, with only 3% of the bluer group members having estimated SFRs below this value. The distribution of sSFR values also mirrors the bimodality seen for the NUV–R colors, and both distributions are clearly continuous, with no gap at intermediate colors or sSFRs.

For the SF galaxies with log ($M_*/M_\odot$) > 8.5, an outlier-resistant least-squares fit\(^7\) to the data in Figure 8 suggests a

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\(^{7}\) Using the \texttt{ladfit} routine in the \texttt{idl}.

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**Figure 7.** Fraction of FUV-detected group members above our UV completeness limit as a function of total stellar group mass (both evaluated within $R_{200}$). Vertical error bars represent Poisson errors on each bin, and color-coding illustrates the mean velocity dispersion within each group stellar mass bin. The partially covered MZ 770 is not included. The inset shows the results (same axis units) when splitting the galaxy sample at the median stellar mass; symbols are the same as in Figure 6.

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

**Figure 8.** Dust-corrected specific SFRs as a function of galaxy stellar mass. Galaxies are color coded according to their UV–optical color, with dotted lines marking characteristic constant SFRs. The dashed line corresponds to an NUV–R color of 4.0 (see Section 3.1), blueward of which galaxies are assumed to be star forming. Galaxies above the dot–dashed line are currently forming stars at >3 times their past average, assuming star formation was initiated at $z = 3$. The histogram shows the distribution of specific SFRs.

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

$$\log \left( \text{SFR}/M_* \right) = -0.46 \log \left( M_*/M_\odot \right) - 5.4,$$  \hspace{1cm} (6)

with a mean absolute deviation of 0.24 dex. The result implies SFR \( \propto M_*^{0.54} \). This is nominally slightly flatter than, but broadly consistent with, the relation obtained from GALEX data of much larger samples of the global low-redshift galaxy population, SFR \( \propto M_*^{0.64-0.65} \) (Salim et al. 2007; Schiminovich et al. 2007).

Some flattening of this relation in groups relative to the field may in fact be expected, if the SFR of low-mass galaxies is suppressed in groups. Indeed, at the median log \( (M_*/M_\odot) = 9.63 \) of the relevant galaxies, Equation (6) would predict a mean sSFR which is 38\%–45\% lower than seen for the field in the above studies (when corrected for differences in the assumed IMF, where necessary). As will be shown, this difference is significant and in excellent agreement with that inferred from the XI data themselves. The important implications are that the mean sSFR of SF galaxies is suppressed in groups relative to the field at a given \( M_* \); and that our estimated SFRs are not significantly biased compared to those derived in other similar studies.

To further explore this suppression in sSFR, we plot in Figure 9 the sSFR of SF galaxies against local environment in equal-number bins. The sample has further been equally split into three bins in stellar mass, to test for systematic dependences for low- and high-mass galaxies separately. Any residual mass dependence within these bins is negligible, as the mean \( M_* \) within each bin varies non-systematically with environment by \( \leq 0.1 \) dex in all three diagrams. Environmental trends are clearly present, particularly for the lowest-mass galaxies, where the mean sSFR declines by 0.4 dex across the region probed. At \( M_* \geq 1 \times 10^{10} M_\odot \), any systematic trends become negligible, however. Hence, not only does the fraction of SF galaxies vary with environment for our sample, but the actual SFR within SF galaxies does so too at fixed galaxy stellar mass \( M_* \gtrsim 10^{10} M_\odot \). Note that, except for the highest-\( M_* \) bin, the suppression of SFR/\( M_* \) is significant out to at least \( R \sim 1.5 \) Mpc \( \approx 2R_{200} \), similar to what is seen for the SF fractions themselves.

To our knowledge, this is the first time such a trend has been reported. No such trends were noticed in our earlier study (when considering galaxies at \( M_*/M_\odot > 10^{9.6} M_\odot \); Bai et al. 2010), plausibly due to poorer statistics, smaller spatial coverage, and the fact that the effect is subtle for galaxies above this mass limit. The result suggests that with the full XI sample, we are now for the first time witnessing the ongoing quenching of star formation within nearby galaxy groups. Hence, such quenching is still taking place in the local universe within the relatively low-mass galaxy structures that dominate galaxy redshift surveys.

3.4. Fraction of Starburst Galaxies

In massive galaxy clusters, infalling galaxies can show enhanced star formation at intermediate radii (e.g., Porter et al. 2008; Pereira et al. 2010), possibly due to interactions with other nearby galaxies. Figure 9 suggests that a similar effect does not occur in smaller groups. To verify this, starburst galaxies were first identified within the groups. In line with our previous analysis of the 24 \( \mu \)m data (Bai et al. 2010), starbursts are here defined as galaxies with a current SFR of at least three times their past average, i.e., with birthrate parameters \( b > 3 \), where

$$b = \frac{\text{SFR}(z = 0.06)}{(\text{SFR})_{\text{past}}} = \frac{\text{SFR} \times \tau}{M_*} (1 - f_R),$$  \hspace{1cm} (7)

and where \( \tau \) and \( f_R \) is the typical stellar age and gas recycling fraction, respectively. Assuming \( f_R = 0.5 \) and \( \tau \) corresponding to a formation redshift \( z = 3 \), just prior to the peak in the cosmic SFR density, the resulting limit of \( b \geq 3 \) is shown as a dot-dashed horizontal line in Figure 8.

The spatial variation in starburst galaxy fraction is illustrated in Figure 10. This plot confirms the absence of a characteristic density or radius at which star formation is enhanced, with fractions declining, within the errors, monotonically and significantly toward group cores. Within the uncertainties, there is also no systematic dependence of the starburst fraction within \( 0-R_{200} \) or \( 1-2 R_{200} \) on total group stellar mass. Hence, the enhanced starburst activity reported around galaxy clusters does not persist into the group regime, not even for the most massive groups in the sample. The unlikely alternative is that any localized enhancement in sSFR occurs at \( R > 2.5 \) Mpc, i.e., partially beyond the \( R \approx 2-3 \) Mpc region identified for clusters (Porter et al. 2008).

Among the group members with \( M_* > 10^{8.5} M_\odot \) (for which our detection of starburst galaxies should be complete), a small fraction \( f_{\text{SB}} = 25/778 \) (3.2\% \( \pm 0.7\%) \) can be classified as starbursts above our UV completeness limit. This is slightly higher than the value of \( f_{\text{SB}} < 1\% \) found for similar-mass
galaxies in our 24 μm data of a subset of the group sample. As demonstrated in Figure 10, the difference is at least partly explicable on account of the larger physical region probed here; for example, the fraction is reduced to 2.4% ± 0.7% within 2R200 and to 1.0% ± 0.6% within R = 0.7 kpc, the region probed by our Spitzer MIPS data in the narrowest direction. The inferred fraction within the full GALEX field is also consistent with the value of fSB = 7.6+3.4−2.5% derived for the local universe by Sargent et al. (2012). The absence of starbursts with M* > 1 × 10^{10} M⊙ in Figure 10 is furthermore consistent with the lack of enhanced star formation seen within groups at z ~ 0.4 down to this mass completeness limit (Balogh et al. 2009).

4. DISCUSSION

The inference that SFR/M* within SF galaxies is environmentally suppressed in groups relative to the field is a novel result, to the best of our knowledge. It suggests that we are directly observing the ongoing quenching of star formation in dense environments. We speculate that this result was not identified in previous group studies for at least three reasons. First, while our group sample is homogeneously selected, the global group properties are very heterogeneous, with groups spanning at least an order of magnitude in velocity dispersion, total stellar mass, richness, and X-ray luminosity (see Table 1 and Rasmussen et al. 2006b, 2010). Combined with the large GALEX field which covers galaxies well into the infall regions, this allows us to self-consistently probe the full range of local and global galaxy environments up to the scale of massive groups. Second, many of these groups are likely dynamically young (Bai et al. 2010) and so contain a significant population of gas-rich SF galaxies which have been only mildly, if at all, affected by the group environment. If much of the environmentally induced gas loss from galaxies, e.g., via starvation, occurs when the group or cluster first collapses (Larson et al. 1980), then the inclusion of such dynamically unevolved systems is crucial for observing SF quenching in action (see also Carollo et al. 2012). Finally, our deep spectroscopy enables inclusion of numerous low-mass galaxies down to M* ≥ 10^8 M⊙, for which environmental effects are found to be particularly prominent. This is only feasible for nearby group samples such as this; other systematic multi-wavelength studies of groups focus instead on systems at intermediate redshifts (e.g., Wilman et al. 2005; McGee et al. 2011) for which the limiting galaxy stellar mass is significantly higher.

4.1. Star Formation and Galaxy Environment

Our results show that both the SF and starbursting galaxy fractions decline toward dense group cores, in general agreement with results for other group samples at low and intermediate redshifts (Balogh et al. 2004; Wilman et al. 2005; Jeltema et al. 2007; McGee et al. 2011) and with those from our 24 μm imaging (Bai et al. 2010). Importantly, the decline in SF fraction is present also at fixed stellar mass, and with galaxies below M* = 10^{9.5–10} M⊙ showing stronger environmental trends than do more massive objects.

Globally, the SF fractions within 2R200 are 35% lower than seen at the largest radii probed. Comparing this to our corresponding 24 μm results for a subset of this sample (Bai et al. 2010) suggests excellent agreement between the UV and mid-IR results, but definitive confirmation of this will have to await the Spitzer results for the full sample (L. Bai et al. 2012, in preparation). In contrast, the observed systematic decline in SF fraction with total group stellar mass was not seen in our preliminary Spitzer analysis, possibly due to poorer statistics and the consideration of a fixed metric region for all groups.

For SF galaxies alone, a systematic suppression of sSFR with local environmental parameters is further seen, persisting out to the largest radii and lowest galaxy densities probed. This is preferentially observed within low-mass galaxies, with the trend becoming negligible at stellar masses M* ≥ 10^9 M⊙, in qualitative agreement with the recent results of Cibinel et al. (2012). At fixed, low galaxy stellar mass, the suppression is also modest, amounting to a factor of ≤2.5 for SF galaxies in the densest group regions (Figure 9). This is much less than the corresponding variation with stellar mass for the same galaxies (∼2 orders of magnitude; see Figure 8). Nevertheless, if taking galaxies at R ≥ 1.5 Mpc = 2R200 as representative of the field and infall regions (see Figures 6 and 9), then the mean and 1σ error on the sSFR of all SF galaxies in these regions is 4.2 ± 0.8 × 10^{-10} yr^{-1}, significantly higher than the 2.8 ± 0.3 × 10^{-10} yr^{-1} found within the group environment itself. Given that the mean stellar mass of the two subpopulations is similar, this implies an average suppression in star formation
activity within all SF galaxies in groups by 34% ± 14% relative to the “field” value within our data. This is in good agreement with the observed ~40% decline relative to typical values for large local galaxy samples discussed in Section 3.3.

The observed environmental variation in sSFR is at odds with the generally negligible difference between typical sSFRs in groups and the field seen in other studies of group samples at low and intermediate redshifts (Balogh et al. 2004; Vulcani et al. 2010; McGee et al. 2011). The inclusion of galaxies well below the $M_* > 3 \times 10^9 M_\odot$ limit of these other studies—afforded by the proximity of our sample—as well as the nature of the XI groups and of the present data (as described above) may all contribute to this difference.

Before interpreting these results, we note that two effects could bias the results in Figures 6 and 9. First, the differences in spectroscopic completeness between the $R \approx 1$ Mpc ICAMACS data and the auxiliary data employed at larger radii imply a relative shortfall of low-mass (i.e., high-sSFR) galaxies at $R \gtrsim 1$ Mpc in the sample. However, this would only act to suppress the observed trends, which could therefore be even stronger than inferred. Second, the presence of interlopers, unaffected by the group environment, would also dampen any real trends. The importance of this can be assessed by quantifying the projected density of SF background galaxies as determined at large radii. To do so, we take galaxies at and beyond the outermost data points in Figures 6 and 9, i.e., those with $\rho_{\text{gal}} < 3$ Mpc$^{-3}$ or $R/R_{200} > 5$, as belonging to the field. In addition, we only consider galaxies with $M_R < -19$, in order to homogenize spectroscopic completeness across all radii. This yields a mean $\Sigma_\delta = 0.7 \pm 0.1$ Mpc$^{-2}$ for the projected density of such SF galaxies in the field. Within the group region ($R \lesssim 2R_{200}$), the corresponding value is $9.6 \pm 1.3$ Mpc$^{-2}$, rising to $\approx 15$ Mpc$^{-2}$ within $R_{200}$. These results do not change if only considering galaxies above our UV completeness limit, suggesting that no more than 5%–7% of the $M_R < -19$ SF galaxies seen within our groups are interlopers.

For fainter galaxies, a larger interloper fraction cannot be ruled out, due to the lower spectroscopic completeness at large radii. However, we do note that the 5%–7% would represent a global upper limit if the fraction of (low-mass, high-sSFR) galaxies fainter than $M_R = -19$ lower in groups than in the field. This assertion would be in line with the observed decline in the dwarf-to-giant galaxy ratio toward cluster cores (Sánchez-Janssen et al. 2008). The tentative implication is that the great majority of SF galaxies identified within the XI groups are physically associated with the group, even those in the densest regions of our most massive groups. In any case, a larger interloper fraction would only act to suppress the observed trends, which are most prominent for the lowest-mass galaxies, so in that sense our results are conservative.

In summary, the dependence of both SF fractions and the sSFRs of SF galaxies on local group environment is a robust result. While the SFRs depend primarily on stellar mass above our UV completeness limit, with SFR $\propto M^{0.5}$, there is a significant residual dependence on local environment at fixed stellar mass. Local galaxy environment thus plays an important role in regulating both the proportion and actual activity of SF galaxies in groups. The fact that the SF galaxy fraction generally declines with increasing total stellar mass suggests that global group environment may also modulate star formation. To explore this possibility, we plot the SF fractions and the sSFR of SF galaxies as a function of $\rho_{\text{gal}}$ in Figure 11 while controlling for global group parameters. To maximize the strength of any trends, the bottom panel only considers the low-mass half of the SF galaxies, for which the dependence of sSFR on local environment is strongest. In this panel, the bin-to-bin variation in mean $M_*$ with environment is $\lesssim 0.2$ dex and not systematically dependent on $\rho_{\text{gal}}$ or $\Sigma_\delta$. The results indicate that, at fixed $\rho_{\text{gal}}$, the SF galaxy fraction and the sSFR of SF galaxies are more heavily suppressed in the cores of high-mass groups with “evolved” central galaxies.

In fact, the trends in Figure 9 are mainly driven by galaxies in the latter groups, since no clear environmental suppression of sSFR is seen for the low-mass groups with blue central galaxies. To understand whether the absence of a trend in the low-mass groups is driven simply by the arguably less evolved systems with blue centrals, we subdivide the low-mass groups according to central galaxy color. Figure 12 shows the resulting mean sSFRs as a function of environment for these two classes of groups. We focus again on the low-mass galaxies only ($M_* < 10^{10.5} M_\odot$), in order to maximize the strength of any trends. While the low-mass groups with red centrals do show mild evidence of a trend with $R$, the mean sSFRs of galaxies within the two types of groups are similar within $R \approx 1.5$ Mpc $\sim 2R_{200}$. Hence within the relevant radii and densities, there is no strong evidence for “less evolved” systems of a given low $M_*$ to behave dramatically differently from those containing red centrals.

The above results suggest that, at fixed local galaxy environment, a residual contribution to quenching is present whose impact scales with total group stellar mass. One caveat to this interpretation is that $\rho_{\text{gal}}$ (and $\Sigma_\delta$) may measure different “environments” in small and large systems, with a given value of $\rho_{\text{gal}}$ being representative of a relatively larger range in $R/R_{200}$ in small systems. However, all trends in Figure 11 are qualitatively similar, and all conclusions unaffected, if instead plotting the results against $R$ or $R/R_{200}$. To further verify that the inferred variations in SF activity at fixed (high) $\rho_{\text{gal}}$ are not just reflecting variations in $\rho_{\text{gal}}$ itself with total group stellar mass, we divide the SF galaxies according to their median $\rho_{\text{gal}}$, consider only galaxies within $R_{200}$, and control for galaxy stellar mass by only considering the low-mass half of the resulting sample. The average sSFR of these galaxies in the two bins of $\rho_{\text{gal}}$ are shown as a function of $M_*$ in Figure 13. A decline with $M_*$ is seen in both bins of $\rho_{\text{gal}}$, confirming that the suppression in SF at fixed local environment does scale with total group stellar mass.

4.2. Quenching of Star Formation in Groups

The immediate interpretation of the above results is that the suppression of SF depends on both local and global group environments, and so is possibly modulated by at least two different mechanisms. Galaxy density, or some quantity scaling with it, plays a role in shutting down SF in groups. Tidal interactions and mergers are plausible candidates, as these should be important in these low-$\sigma$ environments, especially in regions of high galaxy density. In addition, quenching is more efficient at fixed galaxy density in higher-$\sigma$ groups, opposite to what is expected from tidal galaxy–galaxy interactions. If the latter are important, then an additional mechanism whose efficiency is independent of $\rho_{\text{gal}}$ but instead scales with group stellar mass and acts predominantly in the densest regions must also have an impact. Gas-dynamical processes such as ram pressure/viscous stripping and starvation are obvious candidates.

Possible clues to the quenching mechanism emerge from the result that an environmental dependence of sSFR in blue,
SF galaxies at fixed (low) galaxy mass is mainly observed in the more massive groups with red central galaxies, not within the lowest-mass ones with blue centrals. Nor is such a trend observed in massive low-$z$ clusters (Wolf et al. 2009; Chung et al. 2011; Lu et al. 2012), although some evidence is seen when including SF galaxies in $\sigma < 500$ km s$^{-1}$ groups down to $sSFR \approx 10^{-11}$ yr$^{-1}$ (von der Linden et al. 2010). To explain these results, one could hypothesize that the blue SF galaxies observed in low-$z$ clusters, which comprise a significantly smaller fraction than in groups (see Bai et al. 2010), are strongly dominated by interlopers associated with the general field (as supported by the inference that backsplash galaxies in clusters have essentially no SF left after just a single passage through the cluster; Mahajan et al. 2011). Hence, little difference in $sSFR$ between blue field and “cluster” SF galaxies should be expected.

On the other hand, in the smallest and youngest groups (some of which are perhaps collapsing only now) most SF galaxies will be real group members in which star formation may not yet have
been strongly suppressed. Only in relatively massive, evolved groups below the scale of clusters can we directly observe the ongoing environmental quenching of SF.

This raises the possibility of constraining the timescales \( t_q \) for quenching SF in groups. In order to see a correlation between sSFR and clustercentric radius, one needs a coincidence will mainly be interlopers, and the radial trend in SF fraction ("case A") then all SF will be shut down near the virial radius, ongoing environmental quenching of SF.

groups below the scale of clusters can we directly observe the

\[ \Delta_q \approx 5 \text{ Gyr} \times \frac{f_{\text{sb}}}{f_q} \lesssim 0.3 \text{ Gyr} . \]

This timescale is too short in comparison to the crossing times mentioned above. In addition, there is no indication of enhanced SF or starburst activity at small-to-intermediate radii, which could otherwise indicate a temporary boost in SF associated with, or immediately prior to, the actual quenching.

In this context, it is interesting to note the detection of a pronounced bimodality in sSFRs in HCGs (Tzanavaris et al. 2010; Walker et al. 2012), with a sparsely populated region separating low- and high-sSFR systems (<10^{-10.3} yr^{-1} and >10^{-9.9} yr^{-1} respectively; see also Figure 8). This feature is more prominent than seen for our groups, other groups, in the field, or in cluster cores (Walker et al. 2012; Wetzel et al. 2012). It favors a rapid transition from SF to quiescence, perhaps preceded by a period of enhanced SF activity in at least some galaxies. The lack of such a clear bimodality within the XI sample may indicate a slower transition from SF to quiescence than in HCGs, or that SF is not similarly enhanced prior to the transition. The latter possibility may help to explain the lack of a clear enhancement in average sSFR or starburst fraction at intermediate radii for our SF population. Since galaxy–galaxy interactions should be particularly efficient in HCGs, this further supports the idea that other quenching mechanisms are playing a relatively more important role in the XI groups.

In summary, the results inferred from Figure 11, the required quenching timescales in comparison to that associated with an interaction-induced starburst phase, and the comparison to HCGs, all point to galaxy–galaxy interactions being complemented by a more slowly acting quenching mechanism within our groups. Ram pressure stripping and starvation are both likely to act over Gyr timescales in these relatively low-mass environments. The latter process seems particularly promising, as it can still remove hot galactic halo gas even within fairly small groups (Kawata & Mulchaey 2008). Although starvation alone is not expected to act efficiently out to such large radii and low galaxy densities as inferred here, the presence of backsplash galaxies returning to the apocenter of their orbit would help to explain our results. Such galaxies comprise as much as half of all galaxies beyond the virial radius in massive clusters (Balogh et al. 2000). The observed dependence on galaxy stellar mass arises naturally under the assumption that low-mass galaxies are relatively more gas-rich to begin with and have lower gravitational restoring forces, making them more susceptible to gas removal.

4.3. UV Luminosity Density in Groups

As a final point, we consider the total UV luminosity density in the local universe provided by groups similar to those in the XI sample. This is relevant for understanding the contribution of these environments to the local SFR density and hence the general importance of the results presented. To first evaluate the space density of such groups, we consider the catalog of Eke et al. (2004). This is a statistically more robust catalog of groups compiled from the entire 2dFGRS, of which the Merchán & Zandivarez (2002) catalog, from which our groups were drawn, is a subset. As the statistics of the group population in the two catalogs are completely consistent (Rasmussen et al. 2006b), we can reliably use the Eke et al. (2004) catalog for this exercise, benefiting from its superior statistics. Within the full catalog (avoiding the 2dF survey edges and regions of poor completeness), we select groups with \( N_{\text{gal}} \geq 5 \), \( \sigma \leq 500 \text{ km s}^{-1} \), and \( z = 0.05–0.07 \), to mimic the XI selection criteria within a sufficiently wide redshift interval to obtain useful statistics. For the resulting total of 395 systems, we infer a

![Figure 13. Average specific SFR of low-mass (\( M_* < 10^{10.6} M_\odot \)) star-forming galaxies within \( R_{200} \) as a function of total group stellar mass. The sample is divided according to local galaxy density. Results for the high-\( \rho_{\text{gal}} \) bin have slightly displaced along the x-axis for clarity. (A color version of this figure is available in the online journal.)](image-url)
space density of \( n_{\text{XI}} = 3.37 \pm 0.17 \times 10^{-4} \text{Mpc}^{-3} \) (1\( \sigma \) statistical error).

Within \( R = 1 \text{ Mpc} \) of the 22 fully covered groups in the present sample, we derive average specific rest-frame luminosities (prior to dust correction) of \( 3.7 \times 10^{28} \text{erg s}^{-1} \text{Hz}^{-1} \) (FUV) per group. With the space density inferred above, this implies total UV luminosity densities of \( 1.25 \pm 0.06 \text{NUV} \) and \( 0.77 \pm 0.04 \times 10^{25} \text{erg s}^{-1} \text{Hz}^{-1} \text{Mpc}^{-3} \) for such groups. These are factors of 4.2 (4.6) below the total spatially averaged output in NUV (FUV) at \( z < 0.1 \) (Wyder et al. 2005), implying that XI-like groups account for \( 24^{+6}_{-8}\% \) (22\( ^{+3}_{-5}\% \)) of the total NUV (FUV) luminosity density in the local universe. In contrast to the Wyder et al. (2005) results, these numbers do not incorporate corrections for incompleteness below our \( m = 22.0 \) limit and so should be considered lower limits. Hence, despite the enhanced SF quenching in groups relative to the field, at least \( \sim 25\% \) of all UV star formation at low redshift still takes place within friends-of-friends redshift-selected groups similar to the XI systems.

For the 22 groups combined, we further estimate a total UV SFR of SF galaxies within \( R = 1 \text{ Mpc} \) of 180 \( M_{\odot} \text{ yr}^{-1} \), of which 54 \( M_{\odot} \text{ yr}^{-1} \) (30\%) is unobscured. This corresponds to an average \( \text{A}_{\text{FUV}} \approx 1.3 \), in broad agreement with results for both field (Wyder et al. 2005) and cluster samples (Cortese et al. 2008b; Haines et al. 2011). This implies similar levels of mean UV obscuration for galaxies across all types of global environment.

5. SUMMARY AND CONCLUSIONS

Using GALEX imaging, we have presented dust-corrected SFRs and general UV properties of the galaxy population within 23 redshift-selected groups at \( z \approx 0.06 \). The data cover a radius of 2.5 Mpc around each group, allowing us to establish UV properties of group members from group cores into the general field, down to an SFR completeness level of 0.06 \( M_{\odot} \text{ yr}^{-1} \) before dust corrections. Our conclusions may be summarized as follows.

The fractions of UV SF galaxies show a clear, systematic decline toward the dense group cores. The fractions are suppressed by 35\% on average relative to the field, and the suppression is significant out to at least \( R \approx 1.5 \text{ Mpc} \approx 2R_{\text{200}} \). This implies that gas consumption associated with starbursts triggered by galaxy–galaxy interactions proceeds too quickly to be compatible with this timescale. Combined with the absence of a bimodality in the distribution of sSFRs, this result confirms that a more slowly acting mechanism also contributes significantly to quenching in groups.

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