THE STAR-FORMATION-RATE–DENSITY RELATION AT 0.6 < z < 0.9 AND THE ROLE OF STAR-FORMING GALAXIES*

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Received 2010 December 13; accepted 2011 April 7; published 2011 June 16

ABSTRACT

We study the star formation rates (SFRs) of galaxies as a function of local galaxy density at 0.6 < z < 0.9. We used a low-dispersion prism in IMACS on the 6.5 m Baade (Magellan I) telescope to obtain spectra and measured redshifts to a precision of σz/(1 + z) ∼ 1% for galaxies with zAB < 23.3 mag. We utilized a stellar mass-limited sample of 977 galaxies above M > 1.8 × 10^10 M⊙ (log M/M⊙ > 10.25) to conduct our main analysis. With three different SFR indicators, (1) Spitzer MIPS 24 μm imaging, (2) spectral energy distribution (SED) fitting, and (3) [O II]λ3727 emission, we find the median specific SFR (SSFR) and SFR to decline from the low-density field to the cores of groups and a rich cluster. For the SED- and [O II]-based SFRs, the decline in SSFR is roughly an order of magnitude while for the MIPS-based SFRs, the decline is a factor of ∼4. We find approximately the same magnitude of decline in SSFR even after removing the sample of galaxies near the cluster. Galaxies in groups and a cluster at these redshifts therefore have lower star formation (SF) activity than galaxies in the field, as is the case at z ∼ 0. We investigated whether the decline in SFR with increasing density is caused by a change in the proportion of quiescent and star-forming galaxies (SFGs) or by a decline in the SFRs of SFGs. Using the rest-frame U − V and V − J colors to distinguish quiescent galaxies from SFGs (including both unattenuated blue galaxies and reddened ones), we find that the fraction of quiescent galaxies increases from ∼32% to 79% from low to high density. In addition, we find the SSFRs of SFGs, selected based on U − V and V − J colors, to decline with increasing density by factors of ∼5–6 for the SED- and [O II]-based SFRs. The MIPS-based SSFRs for SFGs decline with a shallower slope. The declining SFRs of SFGs with density are paralleled by a decline in the median A_V, providing indirect evidence that the cold gas content that fuels future SF is diminished in higher density environments. The order of magnitude decline in SSFR–density relation at 0.6 < z < 0.9 is therefore driven by both a combination of declining SFRs of SFGs as well as a changing mix of SFGs and quiescent galaxies.

Key words: galaxies: clusters: general – galaxies: clusters: individual (RX J0152.7-1357) – galaxies: evolution – galaxies: formation

Online-only material: color figures

1. INTRODUCTION

Hierarchical structure formation results in more massive dark matter halos assembling at late times. Simulations predict that halos that host L* galaxies, groups, and clusters grow in mass by factors of ∼2–3 between z ∼ 1 and z ∼ 0 (e.g., Wechsler et al. 2002; van den Bosch 2002). At z ∼ 0, these massive halos, or high-density environments, typically host more evolved galaxy populations. The morphological study of Dressler (1980) provided the first quantitative glimpse of this fact, finding elliptical and S0, or early-type galaxies, to dominate in high-density regions of clusters while spirals and irregulars, or late types, dominate at lower densities. This morphology density relation (MDR) has also been found to extend to group environments at z ∼ 0 (Postman & Geller 1984). These high-density environments have continuously accreted galaxies from a range of lower density environments over time. Thus, mass growth in such high-density environments would lead galaxies within newly accreted halos at z ∼ 1 to undergo various transformations in their properties if the general environmental trends at z ∼ 0 hold out to these higher redshifts.

In addition to morphology, other galaxy properties such as rest-frame colors (e.g., Kauffmann et al. 2004; Hogg et al. 2004; Blanton et al. 2005; Baldry et al. 2006) and star formation rates (SFRs; e.g., Abraham et al. 1996; Hashimoto et al. 1998; Gómez et al. 2003; Kauffmann et al. 2004) have also been found to correlate with the local galaxy density at z ∼ 0. Large redshift surveys find such correlations in the field as well, indicating the importance of mechanisms that operate at halo mass scales below that of clusters in transforming galaxy properties at z ∼ 0. In general, the works above find that red, quiescent, early-type galaxies represent a larger proportion of the population in higher density regions at z ∼ 0 such as the cores of groups and clusters, while blue, star-forming, late-type galaxies make up a larger share in lower density regions.
While several studies at $z \sim 0$ have found the mean or median SFRs of galaxies to be lower at higher densities such as in groups and clusters (e.g., Hashimoto et al. 1998; Gómez et al. 2003; Kauffmann et al. 2004), at higher redshifts the direction of this SFR–density trend has been the subject of debate. For luminosity-limited samples, Elbaz et al. (2007) and Cooper et al. (2008) find that at $z \sim 1$ the SFR–density relation reverses, such that galaxies at higher densities have higher SFRs. Meanwhile, for a stellar mass-limited sample at $z \sim 0.8$, Patel et al. (2009a) found the obscured SFR–density relation to decline at higher densities, much like at $z \sim 0$. The direction of the SFR–density trend at $z \sim 1$ has implications for the effectiveness of the various physical processes that operate in different environments in regulating star formation (SF) and evolving galaxies. For example, a reversed SFR–density trend at $z \sim 1$ would imply that the physical processes that lead to the shutdown of SF in high-density group environments produce fewer red, non-star-forming galaxies relative to a declining SFR–density relation.

Studying the origin of the SFR–density relation provides additional insight into the star formation histories (SFHs) of galaxies across a range of environments. For example, a declining SFR–density relation at a fixed stellar mass can be produced by either (1) the proportion of quiescent and star-forming galaxies (SFGs) changing with density, (2) the SFRs of SFGs decreasing at higher densities, or (3) some combination of these two scenarios. The fraction of red and/or blue galaxies are often used to gauge scenario (1) above (e.g., Baldry et al. 2006; Cucciati et al. 2006; Gerke et al. 2007; Cooper et al. 2007; Patel et al. 2009b), however, dusty SFGs can display red optical colors (van der Wel et al. 2007; Maller et al. 2009), thus complicating such measurements. With extinction in galaxies also dependent on environment (Kauffmann et al. 2004), computing the fraction of quiescent galaxies and SFGs versus local density from a single optical color is further complicated. Thus, selecting SFGs, both the unobscured and obscured variety, is essential in determining the contribution of the three scenarios listed above in producing the SFR–density relation.

In this work, we build on our analysis in Patel et al. (2009a) in which we found declining obscured specific SFR (SSFR)–density and SFR–density relations at a fixed stellar mass at $z \sim 0.83$. Here, we expand the analysis with three different SFR indicators in order to confirm these declining relations found in Patel et al. (2009a). Our sample in this work also spans a larger redshift range ($0.6 < z < 0.9$) than in Patel et al. (2009a; $0.8 < z < 0.87$) and encompasses galaxies in several groups and a cluster. As a consequence, we are able to determine how the SFRs of galaxies vary across a range of larger dark matter halos. Finally, one of our primary goals in this work is to determine how the SFRs of individual galaxies change in order to produce the declining SFR–density relation. To this end, we employ a color–color diagram to distinguish quiescent galaxies and SFGs, as also utilized by several other recent works (e.g., Wuyts et al. 2007; Williams et al. 2009).

In conducting this study, we primarily utilize stellar mass-limited samples as opposed to luminosity-limited samples. A limiting magnitude for a survey implies a limiting mass for old, quiescent galaxies that is generally higher than the limiting mass for young SFGs at a given redshift (see, e.g., Appendix A). As a consequence, below the stellar mass limit implied by passive evolution of old systems, no sample can be used to definitively characterize the average galaxy. This does not mean that the lower mass, blue SFGs found in luminosity-limited samples cannot be used to study particular modes of SF, but merely that such samples are not necessarily representative of the full population at low mass. These different selections can therefore lead to widely varying results. For example, in studying the mass-limited MDR in clusters, Holden et al. (2007) found little evolution in the fraction of early-type galaxies at a fixed density between $z \sim 1$ and $z \sim 0$ (see also Holden et al. 2006). An extension of this analysis to field densities also results in a similar conclusion (van der Wel et al. 2007). In contrast, previous results that utilized luminosity-limited samples found a significant buildup of early-type galaxies at late times, with the share of S0s growing at the expense of spirals (e.g., Dressler et al. 1997; Postman et al. 2005). Other galaxy properties correlate with stellar mass as well, such as optical colors (Bell & de Jong 2001; Kauffmann et al. 2003), SFRs (Brinchmann et al. 2004; Salim et al. 2007; Noeske et al. 2007), and extinction (Garn & Best 2010). In drawing conclusions, it is therefore important to consider the distribution of stellar masses for different sub-samples that are being compared.

Our $z$-band spectroscopic selection ($z_{AB} < 23.3$ mag) allows us to build mass-limited samples at $z \sim 0.9$ down to $M > 0.2 M^*$ ($M^* \approx 10^{11} M_\odot$; Fontana et al. 2006), probing an important stellar mass range that is responsible for much of the buildup on the red sequence since $z \sim 1$ (Brown et al. 2007). This relatively low stellar mass limit is a key advantage of our survey over other large spectroscopic field and cluster surveys at these redshifts. For comparison, the stellar mass limit at $z \sim 0.9$ for the $R_{AB} > 24.1$ mag selected DEEP2 survey is $M \approx 5 \times 10^{10} M_\odot$ (see, e.g., Noeske et al. 2007). For the $I_{AB} < 22.5$ mag selected zCOSMOS-bright survey the stellar mass limit is $M \approx 7 \times 10^{10} M_\odot$ (see, e.g., Lilly et al. 2009). For the $I < 23$ mag (Vega) selected EDisCS survey (White et al. 2005), the stellar mass limit is $M \approx 3 \times 10^{10} M_\odot$. The $I_{AB} < 24$ mag selected VVDS-Deep survey (Le Fèvre et al. 2004) reaches a comparable mass limit at $z \sim 0.9$ to that in this work.

Our paper is outlined as follow. In Section 2, we discuss the data used while in Section 3 we derive key quantities such as stellar masses, SFRs, and rest-frame colors. We present our method for distinguishing quiescent galaxies and SFGs in Section 4. Results are presented in Section 5 along with a discussion in Section 6. Finally, a summary is presented in Section 7.

We assume a cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.30$, and $\Omega_\Lambda = 0.70$. Stellar masses and SFRs are based on a Chabrier initial mass function (IMF; Chabrier 2003). All magnitudes are reported in the AB system unless otherwise stated.

2. DATA

2.1. Imaging

2.1.1. Optical and Near-IR Imaging from the Ground

The analysis in this paper is based on imaging from multiple telescopes and instruments that span from the near-UV to mid-IR. We obtained archival Subaru Suprime-Cam (Miyazaki et al. 2002) imaging of RX J0152-13 over a wide field of size $29' \times 39'$ (for a detailed discussion of the Suprime-Cam data, see Kodama et al. 2005). The field was observed in VRIz with Suprime-Cam and had a seeing FWHM $\approx 0.65$ in all four bands. Limiting magnitudes were determined by placing $D = 3\sigma$ apertures across each image and fitting a Gaussian to the distribution of fluxes for the subset of apertures that did not fall on detected sources. The $1\sigma$ width of the Gaussian fit was taken to represent the rms in the background within the aperture. The resulting $5\sigma$
depressions in VRiz were 25.72, 25.65, 25.20, and 24.24 AB mag, respectively \((D = 3''\) aperture). Note that the 3''-band imaging was used for the spectroscopic selection and is discussed below.

We obtained \(K_s\) imaging of the central 26′ × 26′ using the Wide Field Infrared Camera (WIRC; Persson et al. 2002) on the 2.5 m DuPont telescope at Las Campanas. The effective seeing of the mosaic was ~0.7′ and the 5σ depth was 21.22 AB mag \((D = 3''\) aperture). The 3''-band imaging is important for constraining stellar mass estimates, as it samples the rest-frame \(J\) band for most galaxies in our sample. When combined with the optical imaging, the long wavelength baseline afforded by the \(K_s\) data also enables one to constrain the amount of dust extinction.

The Magellan IMACS (Dressler et al. 2006) \(B\)-band imaging covers the full Suprime-Cam field of view. The seeing was 1′.2′ and the 5σ depth was 24.55 AB mag \((D = 3''\) aperture). The \(B\)-band imaging probes the rest-frame UV continuum and therefore provides a measure of the unobscured SFR.

The \(BV\) \(Riz\) imaging is binned to the same pixel scale (0′.2′) and placed on the same astrometric solution. The 3''-band image was used for source detection, and the “double-image mode” of SExtractor (Bertin & Arnouts 1996) was used to extract fluxes in matched apertures in \(BV\) \(Riz\).

2.1.2. Space-based Mid-IR and Optical Imaging

We obtained \(Spitzer\) MIPS (Rieke et al. 2004) 24 μm imaging of the field in Cycles 2 and 5 and combined the data with existing MIPS imaging of the central regions of the field (see Marcillac et al. 2007). The MIPS coverage in this paper with our Cycles 2 and 5 data extends well beyond the region centered on the core of RX J0152-13. These data were also employed in Patel et al. (2009a). The MIPS imaging covers a total of ~0.1 deg \(^2\). We used MOPEX (Makovoz & Khan 2005) to reduce the MIPS data and to create the final mosaic, which had a pixel scale of 1′.245. The point spread function (PSF) FWHM was ~6′. The APEX module in MOPEX was used for source detection. The 5σ detection limit was 125 μJy for a \(D = 6''\) aperture after applying a factor of 3.0 aperture correction to a total flux for point sources. MIPS sources were matched with the \(z_{AB} < 23.3\) mag catalog using a 1.5′′ matching distance. Our choice of matching distance reflects a trade off between the number of matched objects and contamination due to multiple matches. The matching distance is roughly equivalent to two times the rms scatter in the position offset between MIPS objects and objects in the 3''-band catalog. Overall, ~19% of objects from the \(z_{AB} < 23.3\) mag catalog with MIPS coverage are matched to a MIPS source. In cases where multiple objects in the 3''-band catalog could be matched with the same MIPS source, the closest object was assigned as the match. Of the objects assigned to a MIPS counterpart, ~4% of them were assigned in this way. Note that not all galaxies are matched with a MIPS counterpart due to a combination of (1) galaxies with MIPS fluxes that are likely below the detection limit and (2) centroid shifts due to the confusion limit that lead to non-matches (see, e.g., Hogg 2001). The MIPS data are used to derive obscured SFRs as discussed in Section 3.7.

We also used Hubble Space Telescope (HST) Advanced Camera for Surveys (ACS; Ford et al. 2003) imaging that was centered on RX J0152-13. The data reduction procedures are discussed in Blakeslee et al. (2003). The imaging covers regions centered on the cluster core and outskirts \((R \lesssim 6''\) in this paper, we use F625W and F775W imaging of the central regions \((R \lesssim 3''\) and F606W and F814W imaging of the outskirts to make postage stamps (see Section 4).

2.2. Spectroscopy

We selected galaxies with 3''-band MAG_AUTO magnitudes of \(z_{AB} < 23.3\) mag for spectroscopy with IMACS on the Magellan/Baade telescope. Note that this magnitude limit is much brighter than the 3''-band detection limit. In place of the grating, we utilized a low-dispersion prism (LDP) designed by S. Burles for use with the PRIMUS redshift survey (Coil et al. 2010). This configuration allowed us to place ~3000 slits, each with a width of ~0′.8′, onto a single slit mask. The wavelength range of the LDP spectra is ~4500 Å to ~1 μm and spans roughly ~100 pixels. The dispersion and resolution of the LDP vary strongly with wavelength. At 5000 Å, the dispersion is ~20 Å pixel \(^{-1}\) and the spectral resolution FWHM ~80 Å, while at 8500 Å, the dispersion is ~150 Å pixel \(^{-1}\) and the spectral resolution FWHM ~600 Å. The median total exposure time for each object was ~3 hr pixel \(^{-1}\), roughly three times longer than PRIMUS. The spectra were flux calibrated using spectrophotometric flux standards. The data reduction and spectral extraction process for the LDP data are discussed in more detail in S. G. Patel et al. (2011, in preparation).

2.3. Data Preparation for SED Fitting

In preparation for fitting galaxy spectral energy distributions (SEDs), which include both broadband photometry and prism spectroscopy, we took steps to account for differences between the imaging PSFs. For each object, we used a \(D = 3''\) color aperture for the broadband photometry, which was aperture corrected to a total magnitude for all bands using the difference between the 3''-band MAG_AUTO and \(D = 3''\) 3''-band magnitude. While the VRiz\(K_s\) imaging had roughly similar seeing, the \(B\)-band seeing was slightly higher at FWHM ~1′.2′. To account for the larger \(B\)-band PSF, we convolved the \(V\) imaging to the \(B\)-band seeing of 1′.2′ and determined the difference in magnitude for the \(D = 3''\) aperture between the blurred and un-blurred \(V\)-band imaging. This difference (typically ~0.04 mag) was added to the \(D = 3''\) \(B\)-band magnitude to “correct” it to the VRiz\(K_s\) seeing of ~0′.7′.

The LDP spectra were scaled to match the VRiz photometry. The scaling at each LDP pixel was a combination of a constant value plus a wavelength-dependent component, introduced to further improve upon the flux calibration computed from the spectrophotometric standard.

3. ANALYSIS

3.1. LDP Redshifts

LDP redshifts are determined by fitting the SEDs of galaxies with stellar population synthesis models. Both the LDP spectra and broadband photometry are used in the fitting. The method is briefly discussed in Patel et al. (2009b) and will be discussed in more detail in S. G. Patel et al. (2011, in preparation).

Our survey with the LDP finds galaxies spanning a range of redshifts. The analysis in this work focuses on the redshift interval 0.6 < \(z\) < 0.9. The low-redshift boundary was determined such that the bright magnitude selection criterion \((z_{AB} > 18\) mag) would not result in the loss of massive galaxies. Meanwhile, the high-redshift boundary was mostly determined by the desired stellar mass limit of our sample, with some consideration also for the larger redshift uncertainties at higher redshifts.

To determine the precision of the LDP redshifts, \(z_{LDP}\), we compare them to redshifts from higher resolution spectroscopy,
The bottom panel shows a histogram of $\Delta z$ (bottom), with $\Delta z / (1 + z_{\text{spec}})$ as a fraction of $(1 + z_{\text{spec}})$ vs. $z_{\text{spec}}$. Only the 377 galaxies with $0.6 < z_{\text{spec}} < 0.9$ and $z_{\text{AB}} < 23.3$ mag are shown. The 1σ biweight scatter of $\Delta z / (1 + z_{\text{spec}})$ for this sample is $\sigma = 1.2%$. The proportion of catastrophic outliers is very low, with only 1.3% of the sample having $|\Delta z| / (1 + z_{\text{spec}}) > 5%$.

$z_{\text{spec}}$, using the catalogs of Tanaka et al. (2006) and Demarco et al. (2005). We also include redshifts from our own Magellan/IMACS/LDSS3 and Keck/DEIMOS (Faber et al. 2003) spectroscopy in comparing $z_{\text{LDP}}$ to $z_{\text{spec}}$ in Figure 1. For galaxies in our redshift range, $0.6 < z_{\text{spec}} < 0.9$, the LDP redshifts have a biweight scatter of $\sigma_{z_{\text{LDP}} - z_{\text{spec}}}/(1 + z_{\text{spec}}) = 1.2%$. The scatter is approximately the same for blue and red galaxies. Red galaxies have slightly lower $z_{\text{LDP}}$ compared to $z_{\text{spec}} (<1%$ of $(1 + z)$), accounting for the non-zero value of the mode in Figure 1.

In reporting parameters from SED fitting in Section 3.3, we used a different set of templates from those used for determining the redshift. The templates used for determining redshifts utilized specific priors on various components (e.g., $M/L$, rest-frame colors, emission line ratios, etc.) in order to minimize the scatter in $z_{\text{LDP}} - z_{\text{spec}}$. Thus, these templates were used to optimize redshift measurements. In addition, new data products ($B K z$) have been incorporated into our analysis since the redshift determination process, and we have therefore employed more flexible SFHs in fitting these data (see Figure 2).

### 3.2. Spectroscopic Completeness

Understanding the completeness of a spectroscopic survey is critical in reliably computing various quantities, such as local galaxy densities or the typical SFR or fraction of objects of a certain type in a given density bin. We determine the spectroscopic completeness of our $z_{\text{AB}} < 23.3$ mag selected survey as a function of the $z$-band magnitude, $R - z$ color, and position on the sky (see Figure 15 in Appendix B). Overall we obtained a high-quality LDP redshift for 9341 galaxies with $z_{\text{AB}} < 23.3$ mag. At a given position on the sky, the spectroscopic completeness fraction in a magnitude–color bin is determined by taking the number of galaxies with redshift measurements, $z_{\text{LDP}}$, and dividing by the number of galaxies in the same magnitude–color bin from the $z_{\text{AB}} < 23.3$ mag selection catalog. The overall spectroscopic completeness of the survey is $\sim 74%$. The completeness is fairly uniform for bright and faint objects, varying from $\sim 76%$ at $z_{\text{AB}} < 22.5$ mag to $\sim 71%$ at $z_{\text{AB}} > 22.5$ mag. Near the magnitude selection limit, $23$ mag $< z_{\text{AB}} < 23.3$ mag, the completeness is slightly lower ($\sim 60%$–$70%$). The completeness is also uniform in color at $\sim 74%$ for $R - z > 1$ AB mag and $R - z < 1$ AB mag. The completeness is slightly higher in the central regions ($R \lesssim 15'$; $\sim 81%$) compared to the outer regions of the LDP spectroscopy ($R \gtrsim 15'$; $\sim 70%$). Where appropriate, measured quantities are assigned weights based on these completeness maps.

### 3.3. SED Fitting

In order to measure rest-frame properties of our sample, we fit their SEDs with Bruzual & Charlot (2003, hereafter BC03) stellar population synthesis models (low-resolution models), using a Chabrier IMF. The 50th percentile value of $z_{\text{LDP}}$ from
the redshift likelihood function was used as the redshift of each galaxy and the subset of models from our grid (see below) with this redshift were used in the SED fitting. Models were fit to both the LDP spectroscopy and \( BVRIzK_s \) broadband photometry. Due to the IMACS detector response and uncertainty in the flux calibration at redder wavelengths, we utilized the LDP wavelength range of 5000 Å < \( \lambda \) < 8500 Å in the SED fitting.

We used a grid of \( \tau \)-models that span a wide range of galaxy SFHs. Such \( \tau \)-model SFHs are commonly used in fitting SEDs (e.g., Papovich et al. 2001; Förster Schreiber et al. 2004; Franx et al. 2008). The grid consists of four parameters: (1) three metallicities: 0.4 Z\(_{\odot} \), Z\(_{\odot} \), and 2.5 Z\(_{\odot} \), (2) 10 values for \( \tau \) logarithmically spaced between 0.1 Gyr < \( \tau \) < 20 Gyr, (3) 20 ages logarithmically spaced between 0.3 Gyr < \( t \) < 7 Gyr (for a given redshift, ages are limited to the subset with values less than the age of the universe at that epoch), and (4) 10 values for \( A_V \) spaced between 0 < \( A_V \) < 2 and assuming a Calzetti et al. (2000) extinction curve. The stellar component is combined with a Gaussian representative of [O\( \text{II} \)]\( \lambda \)3727 in a non-negative least-squares (NNLS) fit to the SED. In carrying out the SED fitting, several important quantities are stored from the best-fitting minimum \( \chi^2 \) model, including the stellar mass, SFR, and [O\( \text{II} \)] flux from the Gaussian emission line component. Figure 2 shows example fits to SEDs, which include LDP spectroscopy and \( BVRIzK_s \) broadband photometry.

### 3.4. Rest-frame Colors and Magnitudes

We use the procedure described in Rudnick et al. (2003) to apply \( K \)-corrections and determine rest-frame colors and magnitudes. The procedure is commonly used by other works to apply \( K \)-corrections (see, e.g., Taylor et al. 2009; Williams et al. 2009). To determine the magnitude of an object in a desired rest-frame filter, this method uses the redshift to find the two closest observed filters. The observed color of the object from these two filters is used to search the grid of models from the SED fitting for the two models with the closest colors that straddle the observed color. We interpolate in these two models, using the observed color, to determine the magnitude of the object in the desired rest-frame filter. This procedure produces similar colors and magnitudes at \( z \approx 0.8 \) as in Patel et al. (2009a, 2009b), but has the advantage of allowing us to easily expand the analysis to suit the larger redshift range studied in this work. The rest-frame filters relevant to this work are \( UBV \) and Two Micron All Sky Survey \( J \) filter curves supplied with BC03 in computing rest-frame magnitudes.

### 3.5. Stellar Masses

Stellar masses are one of the key parameters computed in the SED fitting. We primarily use a stellar mass-limited sample to conduct our study in this paper. Given the \( z \)-band spectroscopic selection, in our redshift interval of interest, the limiting stellar mass is determined by the masses of the faint red galaxies. Although the \( z \)-band magnitude limit results in blue galaxies with lower masses, their red counterparts of the same low mass do not make it into the sample. We illustrate and discuss this further in Appendix A. We find that the limiting stellar mass at \( z = 0.9 \) is \( M > 1.8 \times 10^{10} \, M_\odot \) (log \( M/M_\odot \) > 10.25). Of the 3326 galaxies in the redshift interval 0.6 < \( z \) < 0.9 with \( z_{\text{AB}} < 23.3 \) mag, 1174 are above the mass limit. Of these, 977 have \( K_s \)-band imaging. About \( \sim 16\% \) of this mass-limited sample with \( K_s \)-band imaging is located in the vicinity of the cluster RX J0152-13 (0.80 < \( z \) < 0.87 and \( R < 3 \) Mpc).

### 3.6. Local Density

We compute the projected local galaxy density using a similar but slightly updated procedure as carried out in Patel et al. (2009a). For a given galaxy at redshift \( z_0 \), we determine the distance to the fifth nearest neighbor, \( d_s \), where only those galaxies above the mass limit of \( \log M/M_\odot > 10.25 \) and with \( \mid z_{\text{neigh}} - z_0 \mid / (1 + z_0) < 2\% \) are included in the neighbor list.

Note that this velocity window is twice as large as the typical uncertainty in \( (1 + z_{\text{LDP}}) \). In determining \( d_s \), distances to all galaxies in the neighbor list are sorted from lowest to highest and the corresponding weights (computed from Figure 15 in Appendix B) of the neighbors from the completeness map are summed. We interpolate to find the distance corresponding to a sum of five in the weights (i.e., \( d_s \)). In this way, our densities reflect values for a survey with 100% spectroscopic completeness. The distance, \( d_s \), is used to define the circular areal element for computing the local density. Thus, the local density is \( \Sigma = 5/(\pi d_s^2) \). The analysis in this paper is limited to the central regions of our spectroscopic coverage (i.e., where there is \( K_s \) or MIPS imaging), therefore minimizing edge effects. In addition, the list of neighbors for objects near the edge of the redshift window containing our sample includes objects that lie slightly beyond the redshift boundaries. The median density of our full mass-limited sample at 0.6 < \( z \) < 0.9 with \( K_s \)-band imaging is \( \sim 6.5 \) Mpc\(^{-2} \). Ignoring galaxies in the redshift interval containing the cluster, 0.80 < \( z \) < 0.87, the median density is \( \sim 4.8 \) Mpc\(^{-2} \).

Figure 3 shows galaxies above the mass limit in three redshift slices and color coded by local density. The cluster RX J0152-13 is at a redshift of \( z \sim 0.83 \) and is easily seen in the center of the bottom panel. Note how this redshift slice, 0.8 < \( z \) < 0.9, contains a significant amount of structure compared to the two lower redshift slices. Another prominent overdensity is the large structure at \( z \sim 0.75 \). We note that Tanaka et al. (2006) identify it as a cluster but measure a velocity dispersion for this structure of only 210 ± 98 km s\(^{-1} \) from a sparse sample of objects. The nature of this overdensity is therefore unclear.

### 3.7. Star Formation Rate Indicators

We use three different measures of the SFR in this paper: (1) rest-frame 12–15 \( \mu \)m luminosities from \textit{Spitzer} MIPS 24 \( \mu \)m imaging, (2) the SFR of the best-fit model from the SED fitting, and (3) [O\( \text{II} \)]\( \lambda \)3727 line luminosities. Each of these SFR indicators has associated with it various systematics (see, e.g., Kennicutt 1998). It is therefore helpful to use multiple indicators in drawing conclusions about the SF activity of galaxies in different environments.

#### 3.7.1. \textit{Spitzer} MIPS 24 \( \mu \)m

The mid-IR emission traced by MIPS in our redshift interval of study (rest-frame 12–15 \( \mu \)m for our sample) represents a combination of thermal emission from dust grains that reprocess UV light as well as emission lines from polycyclic aromatic hydrocarbons (PAHs; see review by Puget & Leger 1989). This mid-IR luminosity correlates with the total infrared luminosity, \( L_\text{IR} \) (8–1000 \( \mu \)m; Chary & Elbaz 2001), which serves as a tracer for the total amount of re-emitted UV-visible light. Typical conversions between \( L_\text{IR} \) and SFR are calibrated with starbursts that have ages of <10\(^8 \) yr (Kennicutt 1998). However, the SF timescales probed by \( L_\text{IR} \) can vary depending on the heating source (e.g., young versus old stars) and optical depth of the dust. Some works find that MIPS-derived SFRs may represent
and thermally pulsing asymptotic giant branch (TP-AGB) stars. This has the effect of overestimating the amount of SF at the epoch of observation given that studies of the SF history of the universe (Lilly et al. 1996; Madau et al. 1996) indicate that SFRs were higher at earlier epochs. Meanwhile, recent Herschel observations indicate that the observed MIPS 24 μm flux by itself underestimates the actual L_{IR} at these redshifts when compared to L_{IR} derived from the PACS 100 μm and 160 μm bands (Rodighiero et al. 2010). The lack of consensus in the literature with regards to SFR measurements derived solely from MIPS 24 μm data is clear. For this reason, we focus on the relative changes in the MIPS-derived SFRs across different environments.

We follow the method of Wuyts et al. (2008) and others (e.g., Damen et al. 2009) in deriving a total infrared luminosity, L_{IR}, from the MIPS data. This technique uses the IR templates of Dale & Helou (2002) to convert the observed 24 μm flux into L_{IR}. For a given redshift, L_{IR} is computed for IR templates spanning a range of heating levels of the interstellar environment. The mean of all log(L_{IR}) is used to represent the final L_{IR}. We note that the derivation of L_{IR} in this work differs from that in Patel et al. (2009a). To convert L_{IR} into an SFR we use Equation (4) from Kennicutt (1998), but adjusted for a Chabrier IMF by multiplying by a factor of 0.56. While active galactic nuclei (AGNs) also emit at these mid-IR wavelengths, they do not contribute significantly to the overall mid-IR luminosity density at these redshifts (Bell et al. 2005). Their contribution to the mid-IR flux for individual galaxies is also not very high (Salim et al. 2009).

In this work, 638 galaxies at 0.6 < z < 0.9 with Ks imaging and stellar masses M > 1.8 × 10^{10} M_☉ have MIPS coverage. The depth of the MIPS imaging precludes a galaxy-by-galaxy analysis as only ~28% of galaxies above the mass limit are detected above 75 μJy. In addition, this detection rate varies for galaxies in different stellar mass and local density ranges. As a consequence, it is not possible to characterize the distribution of individual MIPS fluxes for a given sample with a mean or median, as many galaxies are undetected. In order to compute the median 24 μm flux for a given sample, we therefore stacked MIPS imaging for all galaxies in the sample, combining both detected and undetected sources. This approach allowed us to carry out a uniform analysis across various sub-samples (e.g., mass and density) and enabled us to reach flux levels below the MIPS detection limit. To compute the median MIPS flux and its uncertainty for a given stack, we carry out a bootstrap analysis as follows. For a given sub-sample of N galaxies, we extract postage stamps from the background-subtracted MIPS imaging, centered at the R.A. and decl. of each galaxy. We draw N random postage stamps, with replacement, taking into account the weights from the completeness map, and compute the median of the stack at each pixel position, thus creating a median image from the N postage stamps. Aperture photometry is performed on the median image using an aperture of diameter D = 6′. The resulting flux is aperture corrected and the value stored. This process is repeated 1000 times. The mean and standard deviation of the 1000 measurements for the median are taken to represent the median flux and its uncertainty. These flux values are then converted into an SFR using the median redshift of the sample to determine L_{IR}. This stacking technique was also employed in Patel et al. (2009a). In this work, we build on the analysis from Patel et al. (2009a) by expanding our sample redshift range from 0.80 < z < 0.87 to 0.6 < z < 0.9.

Figure 3. Spatial distribution of galaxies with z_{LIR} in three different redshift slices, 0.6 < z < 0.7 (top), 0.7 < z < 0.8 (middle), and 0.8 < z < 0.9 (bottom). Galaxies above log M/M_☉ > 10.25 are color coded by local density, with divisions for the four density bins at 3, 13, and 50 Mpc, indicated by the blue, green, orange, and red points. Galaxies below this mass limit are shown in gray. The bar at the top right of each panel indicates a projected length of 3 Mpc. An outline of the cluster RX J0152-13 is at z ∼ 0.83 and is indicated by the two solid black circles that represent the virial radius of its two cores. The dashed circle represents a projected clustercentric radius of 3 Mpc.

(A color version of this figure is available in the online journal.)
We compute the median of the stack rather than the mean in order to minimize the contribution from neighboring bright sources. We note that using the mean would have resulted in fluxes that were roughly 0.2 dex larger than what we found for the median. However, the final results would have been qualitatively the same.

In order to test the robustness of the median flux estimates from the stacking analysis, we stacked MIPS imaging of detected objects and found the median stacked flux to agree with the median of the individual flux measurements to within <10%. This was also true for detected MIPS objects in the highest density regions of our sample.

3.7.2. Star Formation Rates from SED Fit

Each BC03 τ-model that is fit to an SED has associated with it an instantaneous SFR. The SFRs derived from the SED fitting primarily leverage the rest-frame UV continuum, sampled by the observed BV filters. Stars above $\sim 5 M_\odot$ dominate the light output at these wavelengths and the SFR measurements are valid for timescales of $10^8$ yr (Kennicutt 1998). Because dust extinction is included in the τ-models, the SED SFRs represent an extinction-corrected SFR. We caution that degeneracies in the parameters of the SED fitting often lead to a range of SFR values for a single galaxy, often dependent on the value of $A_V$.

The typical uncertainty for $A_V$ is 0.3–0.4 mag and was computed by refitting SEDs for a subset of our mass-limited sample after injecting Gaussian noise into the observed flux measurements and comparing the resulting values for $A_V$ with the original ones. We use the SFR from the best-fitting τ-model to represent the SED SFR.

3.7.3. [O ii]λ3727 Emission Line Luminosities

Nebular emission lines serve as a tracer for the SFR as they re-emit UV light blueward of the Lyman limit produced by stars with masses of $> 10 M_\odot$ and lifetimes of $\sim 20$ Myr (Kennicutt 1998). As part of the SED-fitting procedure, we include a Gaussian component for [O ii]λ3727 (see Figure 2), a prominent SFR tracer that lies within the LDP wavelength range for our redshift interval of study. The Gaussian [O ii]λ3727 component is normalized such that the coefficient in the NNLS fit to [O ii] represents the observed line flux, $F_{[O\text{ ii}]}$ (units: erg s$^{-1}$ cm$^{-2}$).

This line flux is converted into a luminosity and then into an SFR using Equation (3) from Kennicutt (1998), and scaled by a factor of 0.56 for a Chabrier IMF.

We estimate extinction-corrected [O ii] luminosities by utilizing the best-fitting $A_V$ from the SED fit and a Calzetti et al. (2000) extinction law. We assume $E(B-V)_{\text{gas}} = E(B-V)_{\text{stars}}/0.44$, as indicated in Calzetti et al. (2000). We caution that these extinction corrections have large uncertainties given the uncertainty in $A_V$ (see the previous section).

In the sections to follow, we discuss SED- and [O ii]-derived SFRs for the 977 galaxies at $0.6 < z < 0.9$ with K$_s$ imaging and stellar masses above log $M/M_\odot > 10.25$. Approximately, $\sim 82\%$ of galaxies in this sample have a non-zero [O ii] flux from the NNLS fit. Note that this sample is larger than the MIPS sample.

4. GALAXY CLASSIFICATION WITH A COLOR–COLOR DIAGRAM: DISTINGUISHING QUIESCENT AND STAR-FORMING GALAXIES

One of the main science goals of this paper is to determine how the SFRs of galaxies vary across a range of environments. In particular, we would like to know how SFGs contribute to the SSFR–density relation. In Patel et al. (2009a), we hypothesized that the change in the median SFR with density was driven simply by a changing proportion of quiescent galaxies and SFGs, as determined from the fraction of red galaxies, leaving a negligible contribution from any change in the SFRs of SFGs with density. Many other works also routinely use the red sequence, as defined with a rest-frame color and magnitude (or stellar mass), to represent quiescent galaxies (e.g., Bell et al. 2004; Faber et al. 2007; Brown et al. 2007). However, dust can lead to a significant fraction of SFGs occupying the red sequence (van der Wel et al. 2007; Maller et al. 2009; Whitaker et al. 2010). Below, we utilize a color–color selection that allows us to identify these reddened SFGs, in addition to blue SFGs, and distinguish both types from quiescent galaxies.

4.1. The UV J Diagram

Figure 4 shows rest-frame $U - V$ versus $V - J$ (hereafter referred to as the UVJ diagram). Such color–color diagrams have been utilized by several other works to distinguish SFGs from quiescent galaxies (Wuyts et al. 2007; Williams et al. 2009, 2010; Wolf et al. 2009; Balogh et al. 2009; Whitaker et al. 2010). The $V - J$ color in particular, with its long wavelength baseline, aids in breaking the degeneracy between age and reddening for red galaxies. One key feature of the UVJ diagram is the red “quiescent clump” ($U - V \sim 2$ AB mag and $V - J \sim 1.3$ AB mag), the sub-sample of red-sequence galaxies that lack SF, as shown later. Below the quiescent clump lies a sequence of SFGs. We use the color boundaries derived by Williams et al. (2009) to separate quiescent galaxies from SFGs. Model BC03 evolutionary tracks are shown for a single stellar population (SSP; red line) and “constant” SFR (CSF; blue line) model ($\tau$-model with $\tau = 20$ Gyr) for solar metallicity. The SSP model track passes near the quiescent clump after $t = 3$ Gyr, while the CSF model track terminates at the blue end of where SFGs lie. The reddening vector in Figure 4(a) shows that SFGs are extended to redder colors with the addition of dust extinction. Note that some of the reddest SFGs ($V - J \gtrsim 1.6$ AB mag) would have been classified as being “red-and-dead” based on $U - V$ colors alone. Instead, these galaxies are distinct from the quiescent clump and are predicted to be SFGs with high values of $A_V$. Bicolor diagrams, such as the UV J ones shown here, can therefore be used to identify SFGs, including those that are reddened.

4.2. A Diversity of Star Formation Histories for UVJ-selected SFGs

While the SSP and CSF model tracks in Figure 4(a) provide a glimpse of how simple galaxy SFHs appear in the UVJ diagram, the actual SFHs of galaxies are likely to be more complex. In Figure 4(a), we also show how a variety of SFHs would appear in the UVJ diagram and emphasize the effectivenes of the Williams et al. (2009) boundary in distinguishing quiescent galaxies and SFGs. These examples also demonstrate that SFGs need not have formed the bulk of their mass recently in order to be classified as an SFG. Even the slightest amount of recent SF can move formerly quiescent galaxies into the SFG region of the UVJ diagram.

SFHs that proceed with several ongoing bursts have been suggested as a mode for galaxies to form a large fraction of their stellar mass, especially at these higher redshifts (Bell et al. 2005; Dressler et al. 2009). The trajectories of various bursting SFHs are shown in Figure 4(a) as dashed lines. The
green and cyan colored tracks show the evolution of a 1% and 5% burst (by mass) added to a 4 Gyr solar metallicity SSP at time steps after the burst, \( t_{\text{AB}} \), of 0.01, 0.1, 0.3, and 0.5 Gyr (time steps shown as squares). Immediately after the burst (i.e., \( t_{\text{AB}} = 0.01 \) Gyr), the \( U-V \) colors become bluer than most SFGs in our sample. After \( t_{\text{AB}} \approx 0.1-0.3 \) Gyr, the colors once again return to resemble a galaxy residing in the quiescent clump. This transition proceeds more quickly for the smaller 1% burst. These models also demonstrate that unreddened bursts on top of old stellar populations are likely not capable of producing SFGs with the reddest colors in the \( UVJ \) diagram. Those red SFGs are most likely to be obscured at some level.

The orange track in Figure 4 represents a 1% burst added to an SSP but with the burst component extinguished by \( A_V = 1 \) mag. Note the displacement from the unobscured 1% burst (green track). These dusty bursts spend even less time (\( <0.1 \) Gyr) classified as SFGs. Depending on the level of extinction and the distribution of the dust, reddened bursts can populate the reddest colors for SFGs.

A galaxy with low levels of continuous SF, qualitatively resembling the state of the Milky Way, is represented by the single yellow star at \( U-V \sim 1.2 \) AB mag and \( V-J \sim 0.9 \) AB mag. This SFH is a combination of a CSF that has been ongoing for the last 1 Gyr and an SSP of age 4 Gyr. The CSF component has produced 5% of the total mass. Such low levels of continuous SF would place a galaxy in the region occupied by SFGs.

SFHs with SFRs that slowly decline with time can lead to galaxies being classified as SFGs despite very low SSFRs, especially for super-solar metallicity stellar populations. The magenta dash-dotted track represents a twice solar metallicity \( \tau \)-model with \( \tau = 1 \) Gyr. Time steps similar to that of the SSP and CSF are shown for this model. The use of a super-solar metallicity model generally results in redder \( V-J \) colors at fixed \( U-V \). After 3–5 e-folding times in the SFR (i.e., between the last two time steps), this \( \tau \)-model would remain classified as an SFG with an SSFR between \( \sim 0.1 \) and 0.02 \( \text{Gyr}^{-1} \). We note that for the corresponding solar metallicity SFH (not shown), the model track would cross the boundary between SFG and quiescent after \( \sim 3 \) Gyr. Thus, some of the galaxies in the “green valley” (1.2 AB mag \( \geq U-V \geq 1.6 \) AB mag) are likely to be comprised of galaxies with somewhat older stellar populations with some ongoing SF, rather than SFGs with more vigorous SF and modest amounts of dust (e.g., \( A_V \sim 1 \) mag).

To summarize, based on BC03 stellar population synthesis models, galaxies classified as star forming in the \( UVJ \) diagram can be comprised of (1) galaxies with relatively constant SFRs since the onset of SF, (2) formerly quiescent galaxies that have undergone a very recent burst, (3) galaxies with some residual, low level, long-term SF (e.g., 5% of mass added over the last 1 Gyr with roughly constant SFR), and (4) super-solar metallicity galaxies with low levels of SF. The addition of dust to any of these scenarios moves SFGs toward redder \( U-V \) and \( V-J \) colors, and generally keeps them in the region occupied by SFGs. Thus, galaxies with virtually any level of recent SF activity would be classified as SFGs, while those without would be classified as quiescent based on the Williams et al. (2009) boundary.

### 4.3. MIPS Detections Trace UVJ-selected SFGs

The models discussed above provide a theoretically motivated backing for the Williams et al. (2009) boundary separating quiescent galaxies and SFGs. Here we perform an empirical check on this boundary. Figure 4(b) shows galaxies with MIPS 24 \( \mu \)m coverage and indicates the subset with 24 \( \mu \)m detections (\( >75 \) \( \mu \)Jy). These detections primarily trace the region occupied by SFGs. Note the detections at red colors (\( U-V > 1.6 \) AB mag) where galaxies would have been considered members of the red sequence based solely on their...
shows a luminosity-selected sample of galaxies at $0.6 < z < 0.9$ with $M_V < -20.5$ AB mag, while the bottom panel shows a mass-selected sample with $\log M/M_\odot > 10.25$. Note that selecting galaxies above a stellar mass limit of $\log M/M_\odot > 10.25$ minimizes the bias against faint red galaxies and therefore results in fewer blue SFGs compared to a luminosity selection. Lines of constant SSFR span from blue $U - V$ and $V - J$ colors to redder ones for SFGs. Thus, SFGs with red $U - V$ and $V - J$ colors indicative of high levels of reddening, perhaps owing to their inclination, can have similar SED-based SSFRs to those with bluer colors. At a fixed $V - J$ color, SFGs with lower SED-based SSFRs have redder $U - V$ colors. The recent SFH of a galaxy therefore also determines where SFGs lie in the $UVJ$ diagram, in addition to the level of extinction. Figure 5 shows that the Williams et al. (2009) boundary separating quiescent galaxies and SFGs is well justified. Note too that although quiescent galaxies with bluer $U - V$ colors ($U - V < 1.7$ AB mag) have somewhat higher SSFRs than redder ones, there are very few galaxies in that region of $UVJ$ color space (see Figure 4(a)).

Finally, it is worth noting that while there appears to be a strong gradient at a fixed $V - J$ color in SED-based SSFRs for SFGs, Williams et al. (2009) find a much smaller range of SSFRs for MIPS-based SFRs. Williams et al. (2010), however, also find a stronger gradient for SED-based SSFRs. These differences between SFR indicators are important to consider when interpreting the results below, especially for the SFRs of SFGs (see Section 5.3).

4.5. A Morphological Overview of the UVJ Diagram

Figure 6 populates the $UVJ$ diagram with $HST$ ACS color postage stamps for a luminosity-limited sample. These high-resolution images provide a sense for how disk- or bulge-dominated systems, and their orientations, help to explain what is seen in different regions of the $UVJ$ diagram. The quiescent region is dominated by galaxies with strong bulge components while the star-forming region is comprised of disks. Blue SFGs appear to be face-on disks and the bluest of them ($U - V \sim 0.7$ AB mag) look like bursting systems—consistent with the location in $UVJ$ color space predicted by the bursting tracks discussed in Figure 4(a). Meanwhile, the reddest SFGs appear to be edge-on disks, consistent with the red colors arising from extinction. Interestingly, several SFGs with intermediate colors ($U - V \sim 1.6$ AB mag and $V - J \sim 1.4$ AB mag) appear to have clear disks but also host a strong bulge component. The colors of these systems likely arise from older stellar populations, perhaps in a transition phase, rather than dust. A more detailed discussion of the morphological structure of galaxies in various environments and in the $UVJ$ diagram will be presented in a future paper (S. G. Patel et al. 2011, in preparation).

4.6. The UVJ Diagram in Different Environments

Our analysis in Section 5 utilizes the $UVJ$ diagram in different density bins in order to examine relative proportions of quiescent galaxies and SFGs as well as the SFRs of SFGs. Figure 7 shows the $UVJ$ diagram in four density bins for galaxies at $0.6 < z < 0.9$ above the mass limit of $\log M/M_\odot > 10.25$. Note the presence of many galaxies with red $U - V$ colors ($U - V \gtrsim 1.7$ AB mag) that are classified as SFGs. For galaxies above the mass limit that would be classified as red-sequence members based solely on their $U - V$ colors (based on a red–blue separation method similar to that applied in Patel

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**Figure 5.** $UVJ$ diagram color coded by the median SED SSFR in color–color bins of size 0.1 mag. (a) Galaxies at $0.6 < z < 0.9$ with rest-frame $M_V < -20.5$ AB mag. (b) Galaxies above a stellar mass of $\log M/M_\odot > 10.25$. The colors that correspond to different log(SSFR) are shown in the bottom right. Bins with fewer than three objects are not included in the analysis. The Williams et al. (2009) boundary separating quiescent galaxies from SFGs is shown in black. Note how selecting by mass minimizes the bias against faint red galaxies and therefore results in fewer blue SFGs compared to the luminosity selection in (a). (A color version of this figure is available in the online journal.)

$U - V$ color. Most of these MIPS detections are in the region of the $UVJ$ diagram consistent with SFGs with extinction. A stacking analysis of the SFGs in this region ($U - V > 1.6$ AB mag) without MIPS detections suggests that they are slightly below the detection limit with a median 24 $\mu$m flux of $\sim 41$ $\mu$Jy and therefore have modest obscured SF activity as well ($\sim 3 M_\odot$ yr$^{-1}$ at $z = 0.75$). In contrast, the median stacked MIPS 24 $\mu$m flux for quiescent galaxies at $U - V > 1.6$ AB mag is a factor of $\sim 3$ lower. The MIPS detections therefore lend further support to our ability to isolate SFGs in the $UVJ$ diagram, including both blue (i.e., unattenuated) and red (i.e., dust reddened) SFGs.

4.4. The Distribution of Star Formation in the UVJ Diagram

The model tracks shown in Figure 4 provide clues on the recent SFHs of galaxies that occupy different regions of the $UVJ$ diagram. However, it is helpful to know how the SFRs or SSFRs of galaxies in our sample are distributed in the diagram, thus providing a check on our division between quiescent galaxies and SFGs. Figure 5 shows the $UVJ$ diagram divided into color–color bins of size 0.1 mag, with each bin color coded by the median SSFR determined from the SED fit. The top panel
et al. (2009b), roughly ∼32% are classified here as $UVJ$-selected SFGs. Balogh et al. (2009) find a similar value at somewhat lower redshifts and for a slightly lower mass limit. Thus, a considerable portion of optically red galaxies in our redshift interval are dusty and star forming.

Figure 7 also indicates the median and standard deviation of the logarithm of the stellar mass in different density bins for our Galaxy sample above the mass limit of $\log M/M_\odot > 10.25$ (black), as well as for the sample of SFGs (blue). The median stellar mass varies by less than $\lesssim 0.15$ dex between different density bins for both samples. The scatter in stellar mass between density bins is also comparable. Given that the distribution of stellar masses in different density bins are roughly similar, mass-dependent correlations with various galaxy properties cannot be solely responsible for any density-dependent correlations (see also Cooper et al. 2010).

5. A DECLINING SSFR–DENSITY RELATION AT $0.6 < z < 0.9$

In this section, we study the SSFR–density relation for galaxies at $0.6 < z < 0.9$ with stellar masses above
Figure 7. $UVJ$ diagram for galaxies at $0.6 < z < 0.9$ with mass $M/M_\odot > 10.25$ in four density bins. The red line denotes the Williams et al. (2009) boundary separating quiescent galaxies and SFGs. Note that selecting galaxies above a mass limit of $M/M_\odot > 10.25$ results in fewer blue SFGs compared to the luminosity-limited selection in Figure 4. The median and standard deviation of $M/M_\odot$ for the full mass-limited sample (black) and of the SFG sample (blue) are labeled in the bottom right for each density bin. The mass function is fairly uniform in different environments for both samples, with slightly more massive galaxies at the highest densities. Mass-dependent correlations for galaxy properties in different density bins are therefore minimized by using a stellar mass-limited sample.

Figure 8. Median SSFR vs. local density for galaxies with mass $M/M_\odot > 10.25$ at $0.6 < z < 0.9$. Gray triangles on the x-axis denote boundaries of density bins. SFRs are derived from three different indicators: (1) rest-frame 12–15 $\mu$m luminosities from $Spitzer$ MIPS 24 $\mu$m imaging (red circles), (2) SED fitting (green squares), and (3) extinction-corrected [O II] 3727 emission line luminosities (blue diamonds). The colored lines indicate the best-fitting log(SSFR)–log(density) relations with corresponding parameters given in Table 1. For all three SFR indicators, the SSFR–density relation decreases from the low-density field to the cores of groups and a cluster. Thus, the SSFR–density relation that we found in Figure 8 is solely responsible for driving the declining SSFR–density relation across the entirety of environments. The SED- and [O II]-based SSFRs decline by a factor of $\sim 4$. We note that the raw [O II] SSFRs that are uncorrected for extinction (not shown), which depend on the SED fits only in establishing a continuum level above which the line flux is integrated, also show a declining SSFR with increasing density, although with a shallower slope ($\Delta \log (SSFR)/\Delta \log (\Sigma) \approx -0.35 \pm 0.05$). This suggests relatively higher levels of extinction at lower densities (see Section 5.4).

A large proportion of our galaxy sample in the highest density environments reside in the vicinity of the cluster. Some of these galaxies have likely passed through the cluster core at some point in time, resulting in their lower SFRs (see, e.g., Balogh et al. 2000). It is therefore reasonable to ask if the cluster is solely responsible for driving the declining SSFR–density relation that we found in Figure 8. Figure 9 shows the mass-limited SSFR–density relation for all three SFR indicators after removing galaxies near the cluster with redshifts in the range $0.80 < z < 0.87$. Removing galaxies in this redshift range

| SFR Indicator | Intercept ($\log (SSFR)$) | Slope ($\Delta \log (SSFR)/\Delta \log (\Sigma)$) |
|---------------|--------------------------|-----------------------------------------------|
| All galaxies (Figure 8) | | |
| MIPS | $-9.61 \pm 0.082$ | $-0.366 \pm 0.072$ |
| SED | $-9.95 \pm 0.099$ | $-0.755 \pm 0.12$ |
| [O II] | $-9.82 \pm 0.078$ | $-0.530 \pm 0.073$ |
| Cluster removed (Figure 9) | | |
| MIPS | $-9.73 \pm 0.096$ | $-0.246 \pm 0.10$ |
| SED | $-9.98 \pm 0.12$ | $-0.653 \pm 0.12$ |
| [O II] | $-9.82 \pm 0.094$ | $-0.534 \pm 0.098$ |
| $UVJ$-selected star-forming galaxies (Figure 12) | | |
| MIPS | $-9.46 \pm 0.086$ | $-0.0787 \pm 0.090$ |
| SED | $-9.61 \pm 0.11$ | $-0.472 \pm 0.11$ |
| [O II] | $-9.42 \pm 0.099$ | $-0.438 \pm 0.10$ |

At $0.6 < z < 0.9$, the SSFR from all three SFR indicators declines across the entire range of densities, from the low-density field to the cores of groups and a cluster. Thus, the overall SF activity in the cores of groups and a cluster at this epoch is lower than in the field. Straight line fits to the MIPS, SED, and [O II] log(SSFR)–log(density) relations indicate non-zero, negative slopes at significances of $\sim 5\sigma$, $6\sigma$, and $7\sigma$. The best-fit parameters are given in Table 1. The SED- and [O II]-based SSFRs decline by roughly an order of magnitude across the full density range, while the MIPS-based SSFRs decline by a factor of $\sim 4$. We note that the raw [O II] SSFRs that are uncorrected for extinction (not shown), which depend on the SED fits only in establishing a continuum level above which the line flux is integrated, also show a declining SSFR with increasing density, although with a shallower slope ($\Delta \log (SSFR)/\Delta \log (\Sigma) \approx -0.35 \pm 0.05$). This suggests relatively higher levels of extinction at lower densities (see Section 5.4).

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primarily impacts the two highest density bins (note the larger error bars). The SSFR–density relation continues to decline at higher densities for all three SFR indicators, although the decline is not as steep for the MIPS-based SFRs. Straight line fits to the MIPS, SED, and \([\text{O} \, \text{II}]\) relations yield non-zero, negative slopes at the \(\sim 2.5\sigma, 5\sigma, \) and \(5\sigma\) levels respectively (see Table 1 for best-fit parameters). Within the uncertainties, the SSFRs of galaxies far from the cluster in the highest density bin are essentially the same as when including the cluster. We note that we arrive at the same conclusion when also excluding the structure at \(z \sim 0.75\). This demonstrates that our result of a declining SSFR–density relation in Figure 8 is general to a range of environments and not solely driven by galaxies near a rich cluster. Galaxies in groups at these redshifts also have lower SSFRs compared to the field.

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

5.1. Does Environment Matter or is Stellar Mass Driving the Declining SSFR–Density Relation?

Higher density environments are found to host more massive galaxies (e.g., Kauffmann et al. 2004; Baldry et al. 2006). Because SFRs and SSFRs are correlated with stellar mass, it is important to account for differences in the distribution of stellar masses between environments in order to determine whether the environment plays an independent role from stellar mass in impacting galaxy SFRs. Utilizing a simple mass cut, as shown in Figures 8 and 9, to first order does a good job of minimizing the differences in the stellar mass distributions between environments (see numbers in Figure 7). Here, we go a step further and study the SSFR–density relation at a fixed mass by dividing our sample into three mass bins. Figure 10 shows the median SSFR versus local density for all galaxies at \(0.6 < z < 0.9\) in three mass bins for SFRs derived from SED fitting and extinction-corrected \([\text{O} \, \text{II}]\). The SSFR–density relations for all three mass bins have negative slopes that are correspondingly very similar. The mass bins in Figure 10 are the same for both SFR indicators and for all mass bins, the SSFR–density relation declines from low to high density for both SFR indicators by roughly an order of magnitude.

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

| Mass Range            | Intercept (log SSFR) | Slope (Δ(log SSFR)/Δ(log Σ)) |
|-----------------------|----------------------|-------------------------------|
| 10.25 < log \(M/M_\odot\) < 10.50 | -9.35 ± 0.19 | -0.810 ± 0.19 |
| 10.50 < log \(M/M_\odot\) < 10.80 | -10.1 ± 0.20 | -0.721 ± 0.16 |
| 10.80 < log \(M/M_\odot\) | -10.2 ± 0.12 | -0.674 ± 0.13 |
| 10.25 < log \(M/M_\odot\) < 10.50 | -9.36 ± 0.14 | -0.660 ± 0.12 |
| 10.50 < log \(M/M_\odot\) < 10.80 | -9.87 ± 0.14 | -0.499 ± 0.13 |
| 10.80 < log \(M/M_\odot\) | -10.1 ± 0.11 | -0.375 ± 0.11 |
significant at $>3\sigma$. Any variation in the stellar mass distribution within a mass bin across different environments would not be sufficient to explain the order of magnitude decline in SSFR found in Figure 10. This confirms that the local environment impacts the median SSFRs and SFRs of galaxies at $0.6 < z < 0.9$ when controlling for stellar mass.

Figure 10 also shows that for the two highest mass bins, the spread in SSFR at a fixed density is fairly small, implying that the SSFR–density relations are comparable. Galaxies in these two mass bins lie above log $M/M_\odot > 10.5$, which is similar to the characteristic mass found by Kauffmann et al. (2003) at $z \sim 0$ above which galaxy properties appear similar. Interestingly, the SSFRs for the highest mass galaxies (log $M/M_\odot > 10.8$) at $0.6 < z < 0.9$ are also sensitive to their local environment, indicating that star formation is not solely responsible for driving their SF properties.

Finally, we note that because the SSFR–density relations are shown for narrow mass bins, the SFR–density relations for a given mass bin have slopes that are similar (in log–log space) to the corresponding SSFR–density relations.

5.2. Quiescent Fraction at $0.6 < z < 0.9$ as a Function of Density

Here, we investigate how a changing proportion of quiescent galaxies and SFGs with density contribute toward the declining SSFR–density relation found in Section 5. Figure 11 shows the fraction of $UVJ$-selected quiescent galaxies at $0.6 < z < 0.9$ as a function of local density using the mass-limited sample. As one might expect from the increasing red galaxy fraction (Patel et al. 2009b) for this sample, galaxies at higher densities are more likely to be in the quiescent clump. The fraction of galaxies in the quiescent clump increases from $32\% \pm 3\%$ at low density to $79\% \pm 4\%$ at high density. The quiescent fraction remains fairly constant across the two lowest density bins, which are representative of the field. The fraction begins to increase substantially between the middle two density bins. Figure 3 shows that these two density bins represent the transition between what are likely filaments, small groups, and the outskirts of larger groups (green) to the centers of large groups and the outskirts of clusters (orange). Several other works at these redshifts also find evidence for a lower fraction of actively star-forming systems in higher density environments, based on Hz emission (Sobral et al. 2011), [O ii] emission (Poggianti et al. 2008), or mid-IR emission (Finn et al. 2010; both emission lines and mid-IR flux at somewhat lower redshifts, e.g., Tran et al. 2009; Balogh et al. 2009).

Finally, we note that when using a similar mass cut as in van der Wel et al. (2007), the quiescent fraction follows the early-type galaxy fraction versus density from that work remarkably well.

5.3. The Role of Star-forming Galaxies in the SSFR–Density Relation

The analysis in Section 5 for all galaxies above the mass limit of log $M/M_\odot > 10.25$ establishes that the median SSFR and SFR decline in higher density environments at $0.6 < z < 0.9$, confirming the declining trend found in Patel et al. (2009a). In the previous section, we found that the changing proportion of quiescent galaxies and SFGs contributes toward the declining SF activity at higher densities. Here, we investigate whether a change in the SFRs of $UVJ$-selected SFGs contributes toward the declining SSFR–density relation.

Utilizing the $UVJ$ diagram (Figure 7), we now select SFGs. Figure 12 shows the SSFR–density relation, derived from all three SFR indicators, for SFGs above the mass limit at $0.6 < z < 0.9$ with $K_s$ imaging. The SSFRs of SFGs decline at higher densities for the SED- and [O ii]-derived SFRs by factors of $\sim 5–6$, while the MIPS-derived SSFRs decline only by a factor of $\sim 1.3$ across the full range of densities. Straight line fits to the MIPS, SED, and [O ii] log(SSFR)–log(density) relations indicate non-zero, negative slopes at significances of $\sim 0.9\sigma$, $4\sigma$, and $4\sigma$ (see Table 1 for best-fit parameters). We note that if galaxies at $0.80 < z < 0.87$ are excluded (i.e., those near the cluster), the MIPS SSFRs for SFGs decline by a factor of $\sim 1.5$ from the lowest to highest densities but the negative slope from a straight line fit ($\Delta \log \text{SSFR}/\Delta \log \Sigma \approx -0.10$) is only significant at the $\sim 1.0\sigma$ level. The decline in the SSFR–density relation, especially for the SED- and [O ii]-derived relations, is therefore driven in part by declining SFRs of SFGs, in addition to
the increasing fraction of quiescent galaxies at higher densities. We note that at a given density the median SSFRs for quiescent galaxies are typically more than an order of magnitude lower than the value for SFGs for a particular SFR indicator and galaxies are typically more than an order of magnitude lower than the value for SFGs for a particular SFR indicator and SFRs of SFGs decline at higher densities, as one would expect if the cold gas supply is diminished in such environments.

Finally, we point out that the \([\text{O} \text{II}]\)-based SFRs rely on the best-fit \(A_V\) from the SED fit, which are highly uncertain. If we instead use a mass-dependent extinction correction for the \([\text{O} \text{II}]\) SFRs from Gilbank et al. (2010), we find a much shallower decline of SSFR with density of only a factor of \(\sim 2\) \((\Delta \log \text{SSFR})/(\Delta \log \Sigma) \approx -0.20 \pm 0.05\). Thus, the method employed for the extinction correction impacts the degree of the decline in SSFR with density.

5.4. A Parallel Decline with Density in Star-formation and Dust Content

SF and dust production are connected since most dust is injected into the ISM through AGB stars or supernovae, both the by-products of recent episodes of SF (see, e.g., Mathis 1990). Subsequent episodes of SF are also dependent on the presence of dust in allowing gas to cool and form stars. With the SFRs of SFGs decreasing with increasing density, we should expect to see less dust associated with SFGs at higher densities.

Figure 13(a) shows the extinction-corrected \([\text{O} \text{II}]\) SFR–density relation for the same sample of SFGs used in Figure 12. A straight line fit to the log(SFR)–log(density) relation gives a slope of \(\Delta \log \text{SFR}/\Delta \log \Sigma \approx -0.33\) and is significant at \(\sim 3.6\sigma\). The decline in SFR from low to high density is a factor of \(\sim 3\), somewhat smaller than the factor of \(\sim 5\) decline in SSFR (Figure 12). However, within the uncertainties on the best-fit slopes, these numbers are compatible. Note also that the median mass is slightly higher at higher densities (see blue numbers in Figure 7), leading to a steeper slope for the SSFR–density relation. The \([\text{O} \text{II}]\)-derived SFRs at high densities could also be overestimated due to AGN activity (see, e.g., Lemaux et al. 2010; Kocevski et al. 2010a), further strengthening the declining SSFR–density and SFR–density trends found here.

Meanwhile, Figure 13(b) shows the median value of the best-fitting \(A_V\) from the SED fits versus density for the same SFGs. The lowest density environments at \(0.6 < z < 0.9\) are associated with the highest dust content, with the median \(A_V\) decreasing by \(\sim 0.5\) mag from low to high density. A straight line fit to the \(A_V\)–log(density) relation indicates a slope of \(\Delta A_V/\Delta \log \Sigma \approx -0.32\) mag dex\(^{-1}\) and is significant at the \(\sim 3.0\sigma\) level. We note that the median \(A_V\) of quiescent galaxies remains constant across all densities, suggesting that the relative differences in \(A_V\) for SFGs are credible. The parallel decline in SFR and \(A_V\) with density for SFGs suggests that the cessation of SF in higher density environments is linked with the level of attenuating dust. The lower dust content at higher density could be a consequence of a physical mechanism removing the dust or a lack of replenishment due to lower levels of SF.

6. DISCUSSION

6.1. No Reversal in the Mass-limited SSFR–Density and SFR–Density Relations at \(z < 1\)

At \(0.6 < z < 0.9\), we find that at a fixed stellar mass, the median SSFR and SFR declines from low- to high-density environments for three different SFR indicators, as also found with MIPS-based SFRs in Patel et al. (2009a). Another new key result is that we find this declining SFR–density relation persists even when excluding galaxies in the vicinity of the cluster (Figure 9), indicating that the declining SFR trend with density applies more generally to all environments. As noted in Patel et al. (2009a), our results differ from that of Elbaz et al. (2007) and Cooper et al. (2008), both of which find a reversal in the SFR–density relation at \(z \sim 1\) for luminosity-limited samples. The reversal found by these other works does not extend to the highest densities probed by their surveys. Instead, their SFR–density relations turnover and decrease at intermediate densities and above. We note however that we do not find any intermediate density regime in which the median SFR is significantly elevated relative to the field. Our results indicate that for galaxies at \(0.6 < z < 0.9\) with stellar masses \(M > 1.8 \times 10^{10} M_\odot\), SF activity in groups and clusters is lower than in the field, similar to what is found at lower redshifts (Wolf et al. 2009) and at \(z \sim 0\) (Kauffmann et al. 2004). Other work at \(z \sim 1\) also finds a declining SFR or SSFR–density relation (e.g., Scoville et al. 2007; Feulner et al. 2007).

The size of the density bins used in this study is fairly broad \((\sim 0.5\) dex). Is it possible that at the intermediate densities where a reversal has been suggested, our density bins lack the resolution required to sample any elevated SF activity? The reversal in Cooper et al. (2008) occurs at overdensities relative to the median density of \(\sim 0.06\) to \(\sim 5\). This translates into a
density range that roughly covers our three lowest density bins. The reversal in Elbaz et al. (2007) extends to densities that are a factor of \( \approx 5-6 \) higher than their lowest densities. This would be encompassed by our two lowest density bins. Any reversal would therefore be observable in our data set even with our broad density bins, but is not.

Our results show that the epoch at which a reversal in the SFR–density relation takes place, if any, is still under debate. Above a mass limit of \( \log M/M_\odot > 10.25 \), we find that the SFR–density relation does not reverse at \( z < 1 \). When studying galaxies at \( z \sim 0.85 \) in a fixed mass range, Cooper et al. (2010) find a larger proportion of red galaxies at high densities compared to low densities. Assuming that these red colors reflect older stellar populations rather than dusty SF, their findings lend support to the declining SFR–density relation found in Patel et al. (2009a) and in this work. The debate also extends to higher redshifts as studies of environment have begun to expand beyond \( z > 1 \). Tran et al. (2010) find evidence for a high fraction of SFGs associated with a cluster at \( z \sim 1.6 \). Also, Hayashi et al. (2010) find [O\textsc{ii}]-derived SFRs for galaxies in a cluster at \( z \sim 1.5 \) that are similar to those of galaxies in the outskirts. In contrast, Gobat et al. (2011) find a well-formed X-ray emitting cluster with a large red elliptical galaxy population at \( z \sim 2 \). Also at \( z \sim 2 \), Tanaka et al. (2010) find the SFRs of galaxies in a proto-cluster to be lower than that of galaxies in the field. Meanwhile, wide-field clustering studies at \( 2 < z < 3 \) find red galaxies to be strongly clustered, suggesting that a color–density relation was in place at those early times with red galaxies dominating more massive halos (Quadri et al. 2007, 2008). These works point out, however, that one key unresolved question is the source of the red colors: dusty SF or old stellar populations. As a follow-up, Quadri et al. (2011) find the fraction of quiescent galaxies, selected with a UVJ diagram similar to ours, to increase with density out to \( z \sim 2 \).

### 6.2. The Origin of the SFR–Density Relation at \( 0.6 < z < 0.9 \)

One of the key questions we set out to answer was how the SFRs of individual galaxies were changing in order to produce the declining SSFR–density relation (Figure 8). Either we are seeing (1) a changing mix of quiescent galaxies and SFGs with increasing density, (2) a decline in the SFRs of SFGs with density, or (3) a combination of the two effects.

From Figure 11, we infer that the fraction of SFGs declines from \( \sim 68\% \) at the lowest densities to \( 21\% \) at the highest densities, a factor of \( \sim 3 \) decrease. If the SFRs of SFGs were to remain constant across various environments, and the SFRs of quiescent galaxies were negligible, then the change in the relative proportion of quiescent galaxies and SFGs with environment would contribute only a factor of \( \sim 3 \) toward the decline in the SSFR–density relation. This amount is less than the order of magnitude decline found in Figure 8 for the SED- and [O\textsc{ii}]-based SFRs, but close to the factor of \( \sim 4 \) decline found for the MIPS-based SFRs. The change in the fraction of quiescent galaxies and SFGs with density therefore cannot be solely responsible for driving the declining SED and [O\textsc{ii}] SSFR–density relations. Indeed, this is what we find in Figure 12, with the SFRs of SFGs declining by factors of \( \sim 5-6 \). The MIPS-based SFRs of SFGs also decline, but by a much smaller amount. Thus, both (1) and (2) above contribute toward the declining SSFR–density relation and potentially reflect a diversity of mechanisms that are responsible for quenching SF on different timescales (see, e.g., Treu et al. 2003; Moran et al. 2007).

Other environmental studies at somewhat lower redshifts also find the SFRs of SFGs to decline at higher densities. For example, using a different color–color selection from our own (in addition to other selection criteria) to identify SFGs, Wolf et al. (2009) found the SSFRs of SFGs to decline at higher densities at \( z \sim 0.17 \). Meanwhile, Poggianti et al. (2008) argue that SF activity in SFGs at \( 0.4 < z < 0.8 \) is independent of local density based on [O\textsc{ii}] equivalent widths. However, a straight line fit to the log(SSFR)–log(density) relation in Figure 7 of Poggianti et al. (2008) indicates a negative slope of \( \Delta \log \text{SSFR}/\Delta \log \text{density} \sim -0.5 \) at a significance of \( \sim 4\sigma \). We note that our definition for SFGs differs from that of Poggianti et al. (2008). Also, while the luminosity-limited sample of Poggianti et al. (2008) is limited to regions in the vicinity of clusters, our survey samples a broader range of environments.

The decline in SFRs with increasing density for SFGs seen in Figure 12 could suggest a gradual shut down in the cold gas supply that fuels SF at \( 0.6 < z < 0.9 \) this is further supported by the decreasing value for \( A_V \) with increasing density. As dust and cold gas are tied to the SF process, the declining \( A_V \) at higher densities suggests less fuel for SF: recent observations of H\textsc{i} deficient spirals in the Virgo Cluster with truncated dust disks (Cortese et al. 2010; De Looze et al. 2010) provide strong support for this view. Other recent works at low redshift also point to the slow removal of gas in order to reproduce various observations (e.g., Weinmann et al. 2009, 2010; van der Wel et al. 2010).

Finally, we note that our selection of SFGs in this work utilizes the color–color space in which they are predicted and observed to occupy. Other works that require the detection of emission lines or mid-IR flux find that such galaxies have relatively little variation in SFR at a fixed mass (intrinsic \( 1\sigma \) scatter of \( \sim 0.3-0.5 \) dex; see, e.g., Brinchmann et al. 2004; Noeske et al. 2007; Rodighiero et al. 2010). Meanwhile, the range in SFRs (SED and [O\textsc{ii}]) for our UVJ-selected SFGs across our three lowest density bins (i.e., environments typically probed by the field surveys above) is roughly \( \sim 0.6 \) dex. Thus, our selection of SFGs and the interpretation of their properties in this work may differ from those of others.

### 6.3. SFRs of SFGs from MIPS versus Other SFR Indicators

The SSFR–density slope for SFGs in Figure 12 for MIPS-based SFRs is much shallower compared to the SED- and [O\textsc{ii}]-based SFRs. Several recent results could explain these findings. For example, while the overall SF activity is clearly diminished in higher density regions, the remaining SF that takes place may occur in a more obscured state. Wolf et al. (2009) find that the few SFGs at high densities at \( z \sim 0.17 \) that remain are predominantly spirals of the reddened variety (see also Gallazzi et al. 2009; Haines et al. 2010). Bekki & Couch (2010) propose that such red, spiral SFGs in higher density environments result from “outside-in truncation,” with the remaining SF taking place in the inner regions of the galaxy where higher gas densities and metallicities lead to heavy obscuration. Another explanation could be that increased AGN activity in high-density regions at these redshifts (Martini et al. 2009) could be responsible for the elevated mid-IR flux. Our LDP spectra lack the resolution necessary to identify Type 2 AGN from emission line diagnostics and therefore such objects likely contaminate our sample. We note, however, that less than \(< 1\% \) of our sample has an X-ray counterpart from the ChAMP point-source catalog (Kim et al. 2007), and ignoring these objects does not impact our results. In addition, Fu et al. (2010) used Spitzer IRS

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spectra to show that objects at $z \sim 0.7$ with MIPS 24 $\mu$m fluxes less than $\sim 1$ mJy, as is the case with our entire sample, are dominated by SF rather than AGN activity. Finally, the shallow decline of SSFR with density for SFGs in Figure 12 from the MIPS-based SFRs may reflect the potentially longer timescales probed by that SFR indicator (see, e.g., Salim et al. 2009; Kelson & Holden 2010). High-density regions accrete galaxies from lower densities where the typical SFRs are much higher. If an SFR indicator traces SF over long timescales, the median SFR for a sample of galaxies at high densities will be higher given that the newly accreted galaxies from low density will still register high SFRs. Lending further support to this explanation is the finding that MIPS 24 $\mu$m detected sources at high densities at these redshifts exhibit strong Balmer absorption (Kocevski et al. 2010b). This would indicate a substantial population of A stars of age $\sim 1$ Gyr old, a timescale in accord with the findings of Salim et al. (2009) and Kelson & Holden (2010).

7. SUMMARY

We have carried out a wide-field spectroscopic survey of galaxies at $0.6 < z < 0.9$ that span a range of environments, including the low-density field, groups, and the $z \sim 0.83$ cluster RX J0152-13. We selected galaxies with $z_{\text{AB}} < 23.3$ mag for spectroscopy with IMACS on Magellan with a low-dispersion prism (LDP). These LDP spectra yielded redshifts with a remarkable precision of $\sigma_z/(1 + z) \sim 1\%$.

We used a mass-limited sample above log $M/M_\odot > 10.25$ to study the SFRs of galaxies as a function of the local galaxy density. Above the mass limit, the distribution of stellar masses in different density bins in our sample is very similar (Figure 11). Thus, the environmental trends reported in this paper are not significantly affected by any residual correlation with stellar mass.

Given the systematics associated with any single SFR indicator, we used three different SFR indicators in drawing conclusions about the environments at $0.6 < z < 0.9$ where SF is quenched. We computed SFRs from (1) rest-frame 12–15 $\mu$m luminosities measured with Spitzer MIPS 24 $\mu$m imaging, (2) SED fitting, and (3) extinction-corrected $[O\,\text{II}]\lambda 3727$ luminosities from the LDP spectra.

To distinguish SFGs from quiescent galaxies, we used a $U - V$ versus $V - J$ diagram (referred to here as the $UVJ$ diagram) to determine whether the SFR–density relation at $0.6 < z < 0.9$ was driven by (1) a change in the proportion of quiescent galaxies and SFGs or (2) a change in the SFRs of SFGs in different environments. The $UVJ$ diagram is especially useful in isolating dusty, SFGs on the red sequence, which would otherwise be classified as quiescent based on a single optical color (Figures 4 and 6).

Our main results are the following.  

1. With three different SFR indicators, we find that the median SFR–density relation at $0.6 < z < 0.9$ declines across the entire range of densities probed: from the low-density field to the cores of groups and a cluster (Figure 8). The declining SFR–density relation holds even when removing galaxies near the cluster (Figure 9). The declining SFR–density relation is therefore general to all environments at these redshifts and not driven by galaxies located near the rich cluster in our sample.

2. For fixed mass bins, the SFR–density shows a clear decline with increasing density (Figure 10), confirming that the local environment is indeed a factor in impacting the SFRs of galaxies when controlling for mass. This result also implies that at a fixed mass the SFR–density relation at these redshifts follows a similar decline with increasing density.

3. The fraction of quiescent galaxies increases by a factor of $\sim 2.5$, from $\sim 32\%$ to $\sim 79\%$, between the lowest and highest densities (Figure 11). We note that these quiescent fractions are similar to the morphological early-type fractions seen in van der Wel et al. (2007) when adjusting for the mass selection. We also find that the SSFRs of SFGs decline with density (Figure 12). The declining SFR–density and SSFR–density relation at $0.6 < z < 0.9$ can therefore be attributed to a combination of (1) a changing mix of quiescent galaxies and SFGs and (2) a decline in the SFRs of SFGs with increasing density.

4. In parallel with the declining SFRs of SFGs, the median $A_V$ of SFGs also declines at higher densities (Figure 13(b)). This decline in $A_V$ signifies a lack of cold gas and therefore the quenching of SF in higher density environments.

In future work, we plan to use HST ACS and WFC3 imaging to determine how SF activity is distributed within SFGs in different environments. Such an analysis will lead to insights on whether SF is being turned off across the entire galaxy (e.g., via starvation) or only in the outer regions (e.g., gas stripping). The answer has implications for the mechanisms that are responsible for regulating SF in galaxies residing in different environments at half the age of the universe.

We thank Sandra Faber and David Koo for helpful discussions. We also thank Stijn Wuyts for providing a table for converting MIPS 24 $\mu$m fluxes into total infrared luminosities. We also wish to acknowledge those who have contributed to the construction and deployment of IMACS as well as Scott Burles for developing the low-dispersion prism, and the PRIMUS collaboration for allowing us to investigate galaxies with their hardware. This research was supported by NASA grant NAG5-7697, Spitzer grants JPL 1277397 and JPL 1344481, as well as an NWO-Spinoza Grant.
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Panel (a) shows the completeness within an ellipse centered at $z_{AB} = 23.3$ mag as a function of redshift for galaxies at $0.6 < z < 0.9$ and with $K_s$ imaging. Using the $UVJ$ diagram (see Figure 4), we identify quiescent galaxies and denote them as red circles in the figure. SFGs are shown as open blue diamonds. Note how SFGs extend to low masses where low mass quiescent counterparts are lacking. In order to study a representative stellar mass-limited sample of quiescent galaxies and SFGs the mass limit will then be determined by the redder quiescent galaxies. The solid line shows the stellar mass for an old stellar population formed at $z_f = 4$ and observed to have a magnitude of $z_{AB} = 23.3$ mag at all redshifts. Note that a similar galaxy with a fainter magnitude would fall below this line. For a quiescent galaxy in our sample at $z_{AB} = 23.3$ mag (i.e., our survey magnitude selection limit), the limiting stellar mass at $z = 0.9$ is $\log M/M_\odot > 10.25$ (dashed line). This value represents the limiting stellar mass for galaxies in the redshift interval studied in this paper, $0.6 < z < 0.9$.

**APPENDIX A**

**STELLAR MASS LIMIT OF THE SAMPLE**

We primarily use a stellar mass-limited sample to conduct our study. Figure 14 illustrates how we determine our mass limit. The figure shows the stellar masses of galaxies with $z_{AB} < 23.3$ mag as a function of redshift for galaxies at $0.6 < z < 0.9$ and with $K_s$ imaging. Using the $UVJ$ diagram (see the text for precise boundaries of each region). The overall completeness for each region is indicated in the top left of each panel. A color bar corresponding to the completeness fraction is shown in the top left. We note that the $R - z$ magnitudes represent Vega–AB mag as the raw data were zero-pointed using the system that was native to each filter ($R_{AB} = R_{Vega} + 0.185$ mag). Each panel also shows the $R - z$ color and $z$-band magnitudes of galaxies in the given region at $0.6 < z < 0.9$, giving a sense for where most of our sample lies in these completeness maps.

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

**APPENDIX B**

**SPECTROSCOPIC COMPLETENESS**

In making various measurements in this paper, we have taken care to account for variations in the spectroscopic completeness of our survey. The completeness here is defined as the ratio of the number of galaxies with a high-quality LDP redshift to the number of galaxies in the $z$-band selection catalog. The reciprocal of the completeness fraction is used as a weight when computing quantities such as the local galaxy density, median SSFRs, etc. Figure 15 shows the spectroscopic completeness as a function of the observed $R - z$ color and $z$-band magnitude. Panel (a) shows the completeness within an ellipse centered on R.A. $= 28:1814$ and decl. $= -13:9998$, with axis lengths $a_{R.A.} = 0.174$ and $b_{decl.} = 0.132$. Panel (b) shows the completeness in the outer regions with the same R.A. and decl. but with $a_{R.A.} = 0.29$ and $b_{decl.} = 0.22$. In general, the inner

region has a slightly higher level of completeness. Overplotted on each completeness map are the colors and magnitudes of objects within the given region and with redshifts in the range $0.6 < z < 0.9$. The bulk of our sample lies in regions of completeness space that are relatively smooth.
