TRIGGERED STAR FORMATION IN GALAXY PAIRS AT $z = 0.08–0.38$

Deborah Freedman Woods1, Margaret J. Geller2, Michael J. Kurtz2, Eduard Westra2, Daniel G. Fabricant2, and Ian Dell’Antonio3

1 Department of Astronomy, Harvard University, Cambridge, MA 02138, USA; dwoods@cfa.harvard.edu
2 Smithsonian Astrophysical Observatory, Cambridge, MA 02138, USA
3 Department of Physics, Brown University, Providence, RI 02912, USA

Received 2009 May 23; accepted 2010 February 9; published 2010 April 6

ABSTRACT

We measure the strength, frequency, and timescale of tidally triggered star formation at redshift $z = 0.08–0.38$ in a spectroscopically complete sample of galaxy pairs drawn from the magnitude-limited redshift survey of 9825 Smithsonian Hectospec Lensing Survey galaxies with $R < 20.3$. To examine the evidence for tidal triggering, we identify a volume-limited sample of major ($|\Delta M_R| < 1.75$, corresponding to mass ratio $> 1/5$) pair galaxies with $M_R < -20.8$ in the redshift range $z = 0.08–0.31$. The size and completeness of the spectroscopic survey allow us to focus on regions of low local density. The spectrophotometric calibration enables the use of the 4000 Å break ($D_n4000$), the Hα specific star formation rate (SSFRHα), and population models to characterize the galaxies. We show that $D_n4000$ is a useful population classification tool; it closely tracks the identification of emission line galaxies. The sample of major pair galaxies in regions of low local density with low $D_n4000$ demonstrates the expected anti-correlation between pairwise projected separation and a set of star formation indicators explored in previous studies. We measure the frequency of triggered star formation by comparing the SSFRHα in the volume-limited sample in regions of low local density: $32\% \pm 7\%$ of the major pair galaxies have SSFRHα at least double the median rate of the unpaired field galaxies. Comparison of stellar population models for pair and for unpaired field galaxies implies a timescale for triggered star formation of $\sim 300–400$ Myr.

Key words: galaxies: active – galaxies: interactions – galaxies: stellar content

Online-only material: color figure, machine-readable and VO tables

1. INTRODUCTION

Hierarchical galaxy formation models predict frequent interactions in a galaxy’s history (e.g., Cole et al. 2000; Wechsler et al. 2002). Some of these interactions may trigger star formation. Observational limits on the frequency and duration of triggered star formation are an important constraint on the role of these interactions in the evolution of stellar populations.

Evidence that galaxy interactions at low redshift trigger star formation was first detected in photometric observations by Larson & Tinsley (1978) who demonstrated that apparently interacting galaxies in the Atlas of Peculiar Galaxies (Arp 1966) have a broader range of colors and tidal features than typical galaxies. Spectroscopic indicators confirm that interacting galaxies tend to have enhanced star formation rates (SFR; Kennicutt & Keel 1984; Kennicutt et al. 1987; Keel 1993; Liu & Kennicutt 1995a; Donzelli & Pastoriza 1997; Barton et al. 2000, 2003; Lambas et al. 2003; Nikolic et al. 2004; Kauffmann et al. 2004; Woods et al. 2006; Woods & Geller 2007; Ellison et al. 2008). Infrared observations (Kennicutt et al. 1987; Jones & Stein 1989; Sekiguchi & Wolstencroft 1992; Keel 1993; Nikolic et al. 2004; Geller et al. 2006; Smith et al. 2007) and radio observations (Hummel 1981) yield similar results. Observations that galaxy pairs with the smallest project separation have the highest SFRs provide direct evidence for triggered star formation (e.g., Barton et al. 2000).

Recent studies show that galaxy interactions at intermediate redshift trigger star formation. Measurements of infrared luminosity (Lin et al. 2007) and EW([O II]) (de Ravel et al. 2009) indicate an anti-correlation between projected separation and star formation activity for pair galaxies at intermediate redshift ($z < 1$), similar to the trend observed at low redshift. Analysis of the morphology of intermediate redshift ($z = 0.1–0.6$) pair galaxies likewise shows an increase in the fraction of asymmetric galaxies in pairs, an indication of tidal interaction (Patton et al. 2005).

Although observations demonstrate that galaxy interactions can lead to enhanced star formation activity, the results of studies of the frequency and intensity of star formation activity appear to vary with the sample selection. Li et al. (2008) found that 30% of the SDSS pair galaxies with high specific star formation rates (SSFRs) have a companion within 100 kpc, and that low to average SSFR galaxies rarely have a companion. In a separate study of SDSS pair galaxies at $z < 0.16$, Ellison et al. (2008) measured up to 40% enhancement in the median SFR of close pair galaxies with stellar mass ratios $< 1/10$ relative to their comparison sample of non-pair systems. Bergvall et al. (2003) found that global $UBV$ colors do not show significant enhancement in star formation in their small sample of interacting galaxies compared to isolated systems. However, they do find that SFRs at the very centers of the interacting systems are increased by a factor of $\sim 2–3$ over the non-interacting systems. Spitzer infrared observations of 35 tidally disturbed Arp galaxies show that their 24 μm emission is more centrally concentrated than in normal spiral galaxies, suggesting a build up of central gas which could fuel central star formation; their infrared colors suggest an increase in the mass normalized SFR by a factor of 2 over the normal spirals (Smith et al. 2007).

Numerical simulations account for the observed range of strength, frequency, and duration of triggered star formation. In the large suite of simulations by Di Matteo et al. (2008), galaxy interactions and mergers produce only moderate star formation enhancement relative to non-interacting galaxies at
low redshift. Strong starbursts are rare and short lived, typically lasting a few hundred Myr. The duration of the starburst declines as the enhancement in SFR increases.

Global galaxy properties affect their susceptibility to tidally triggered star formation. Systems with sufficient gas can exhibit triggered star formation in major interactions (e.g., Mihos & Hernquist 1996; Tissera et al. 2002; Cox et al. 2006; Di Matteo et al. 2007). Interactions between gas-poor galaxies (“dry mergers”) produce little or no star formation, although they contribute substantially to the build-up of massive galaxies (e.g. Tran et al. 2005; Van Dokkum 2005; Cattaneo et al. 2008). Internal structure strongly affects the susceptibility to gaseous inflows; late-type galaxies without strong bulge components are more likely to have bar instabilities that drive the gaseous inflows powering the central star formation (Mihos & Hernquist 1996; Di Matteo et al. 2007).

The relative mass of the galaxy compared to its neighbor and the intrinsic mass also influence the degree of triggered star formation. Galaxy pairs of similar mass (luminosity) show strong enhancement to their SFRs in both members of the pair in both observational (Woods & Geller 2007; Ellison et al. 2008) and theoretical (Cox et al. 2008) studies. Observations show that although satellite galaxies occasionally experience triggered star formation, the brighter of a high mass (luminosity) ratio pair does not undergo significant tidal triggering (Woods & Geller 2007); numerical simulations suggest a similar picture (Cox et al. 2008). The intrinsic mass of the galaxy also plays a role: low mass (luminosity) galaxies in major mergers are more strongly affected by the interaction than are high mass galaxies in major mergers in observations of pair galaxies (Woods & Geller 2007; Ellison et al. 2008).

Local environment can affect star formation activity in a galaxy apparently independent of an interaction. Galaxies in clusters and large groups tend to have redder color and less current star formation than isolated systems (e.g., Hubble & Humason 1931; Cooper et al. 2007; Gerke et al. 2007). Barton et al. (2007) show that pair galaxies are more common in regions with greater local density than the unpaired galaxies. Including pair galaxies from high density regions suppresses the signal of triggered star formation measured in comparison to unpaired galaxies.

We take advantage of the size and completeness of the Smithsonian Hectospec Lensing Survey (SHELS; Geller et al. 2005, 2010) galaxy sample to identify a set of major interactions at z = 0.08–0.38 for galaxies with young stellar populations in regions of local density, where we can measure the cleanest signal of triggered star formation. Local density selection at intermediate redshift has not been possible before this sample.

The stability of the Hectospec instrument enables accurate spectrophotometric calibration of the spectra. The calibrated spectra provide the 4000 Å break (D4000) and the Hα SSFR (SSFRHα), which we use to characterize the star formation. We quantify the frequency, strength, and timescale of triggered star formation in major galaxy interactions using measurement of SSFRs and stellar population models fitted to the individual spectra.

We describe the SHELS data in Section 2 and the sample selection in Section 3. Section 4 describes spectroscopic classification metrics, including the identification of strong active galactic nuclei (AGNs) and the use of the spectroscopic indicator D4000 as a classification tool. We consider local density effects in Section 5. Section 6 describes various measurements of tidally triggered star formation, including the frequency, strength, and timescale of enhanced star formation activity. Throughout this study we assume standard ΛCDM cosmology, where H0 = 71 km s^{-1} Mpc^{-1}, Ωm = 0.3, and ΩΛ = 0.7 (Spergel et al. 2003).

2. DATA

In this section, we describe the SHELS data set. We give an overview of the data set in Section 2.1. We describe the photometric measurements in Section 2.2, and the spectroscopic measurements in Section 2.3, including the SSFRHα in Section 2.3.1, and aperture effects in Section 2.3.2.

2.1. Smithsonian Hectospec Lensing Survey

The SHELS magnitude-limited redshift survey includes 9825 galaxies with total R-band magnitude R < 20.3. The galaxies are selected from the Deep Lens Survey F2 field R-band images (DLS; Wittman et al. 2002, 2006). We obtained spectroscopy using Hectospec (Fabricant et al. 2005) at the MMT. The spectroscopic sample is 97.7% complete to R = 20.3, and the differential completeness at the magnitude limit is 94.6%.

We restrict our analysis to the 6935 galaxies with redshift z = 0.080–0.376. The lower redshift limit minimizes aperture effects (Section 2.3.2) and the upper limit allows measurement of the Hα flux (Section 2.3).

The DLS F2 field covers 4 deg^2 on the sky centered on R.A. = 9h19m32.4s, decl. = +30°00′00″ (J2000). The Sloan Digital Sky Survey (SDSS; Adelman-McCarthy et al. 2006) also covers this region.

The DLS images come from the Kitt Peak Mayall 4 m telescope with the Mosaic prime-focus imager (Muller et al. 1998). The DLS observed in the R band during nights with seeing ≤0.9. The 1σ limiting surface brightness in R band is 29 mag arcsec^{-2}. The DLS also observed in V band.

The 0.9 resolution of the DLS R-band images allows identification of close pairs or merging galaxies with minimum separations of 15–20 kpc up to z ≤ 0.3. The median seeing for the SDSS photometry is 1.4 point-spread function (PSF) in r band (Adelman-McCarthy et al. 2006). Thus some systems that cannot be distinguished in the SDSS data can be identified in the DLS. A total of eight pairs in the DLS are missing from SDSS.

Objects with stellar light profiles, i.e., AGNs at high redshift, may be preferentially excluded from our sample because DLS objects with stellar light profiles are not targeted for spectroscopy. However, with the DLS 29 mag arcsec^{-2} surface brightness limit and the 0.9 resolution, we should be able to detect bright host galaxy bulges to the limiting z = 0.376. We discuss AGN detection in more detail in Section 4.1.

The Hectospec observations identify a spectroscopic pair of emission line galaxies at R.A. = 9h16m58.903, decl. = +29°43′10.597 (J2000). The image, which shows a double-nuclei extended object, and the spectra are available on our Web site.4 We do not include this object in our analysis because the selection of spectroscopic pairs is not complete or uniform.

Only 230 galaxies in our sample lack spectra (2.3%). Of these, ~24 galaxies (10%) may be members of pairs that satisfy our criteria for analysis (Section 3). The fraction of galaxies in pairs in our sample as a whole is ~10% (Section 3).

2.2. Photometric Measurements

Image processing for the DLS uses the IRAF package DLS image processing for the DLS uses the IRAF package DLS. We take advantage of the size and completeness of the Smithsonian Hectospec Lensing Survey (SHELS; Geller et al. 2005, 2010) galaxy sample to identify a set of major interactions at z = 0.08–0.38 for galaxies with young stellar populations in regions of low local density, where we can measure the cleanest signal of triggered star formation. Local density selection at intermediate redshift has not been possible before this sample.

The stability of the Hectospec instrument enables accurate spectrophotometric calibration of the spectra. The calibrated spectra provide the 4000 Å break (D4000) and the Hα SSFR (SSFRHα), which we use to characterize the star formation. We quantify the frequency, strength, and timescale of triggered star formation in major galaxy interactions using measurement of SSFRs and stellar population models fitted to the individual spectra.

We describe the SHELS data in Section 2 and the sample selection in Section 3. Section 4 describes spectroscopic classification metrics, including the identification of strong active galactic nuclei (AGNs) and the use of the spectroscopic indicator D4000 as a classification tool. We consider local density effects in Section 5. Section 6 describes various measurements of tidally triggered star formation, including the frequency, strength, and timescale of enhanced star formation activity. Throughout this study we assume standard ΛCDM cosmology, where H0 = 71 km s^{-1} Mpc^{-1}, Ωm = 0.3, and ΩΛ = 0.7 (Spergel et al. 2003).

The DLS F2 field covers 4 deg^2 on the sky centered on R.A. = 9h19m32.4s, decl. = +30°00′00″ (J2000). The Sloan Digital Sky Survey (SDSS; Adelman-McCarthy et al. 2006) also covers this region.

The DLS images come from the Kitt Peak Mayall 4 m telescope with the Mosaic prime-focus imager (Muller et al. 1998). The DLS observed in the R band during nights with seeing ≤0.9. The 1σ limiting surface brightness in R band is 29 mag arcsec^{-2}. The DLS also observed in V band.

The 0.9 resolution of the DLS R-band images allows identification of close pairs or merging galaxies with minimum separations of 15–20 kpc up to z ≤ 0.3. The median seeing for the SDSS photometry is 1.4 point-spread function (PSF) in r band (Adelman-McCarthy et al. 2006). Thus some systems that cannot be distinguished in the SDSS data can be identified in the DLS. A total of eight pairs in the DLS are missing from SDSS.

Objects with stellar light profiles, i.e., AGNs at high redshift, may be preferentially excluded from our sample because DLS objects with stellar light profiles are not targeted for spectroscopy. However, with the DLS 29 mag arcsec^{-2} surface brightness limit and the 0.9 resolution, we should be able to detect bright host galaxy bulges to the limiting z = 0.376. We discuss AGN detection in more detail in Section 4.1.

The Hectospec observations identify a spectroscopic pair of emission line galaxies at R.A. = 9h16m58.903, decl. = +29°43′10.597 (J2000). The image, which shows a double-nuclei extended object, and the spectra are available on our Web site.4 We do not include this object in our analysis because the selection of spectroscopic pairs is not complete or uniform.

Only 230 galaxies in our sample lack spectra (2.3%). Of these, ~24 galaxies (10%) may be members of pairs that satisfy our criteria for analysis (Section 3). The fraction of galaxies in pairs in our sample as a whole is ~10% (Section 3).

2.2. Photometric Measurements

Image processing for the DLS uses the IRAF package DLS image processing for the DLS uses the IRAF package DLS.
calibration. Wittman et al. (2006) construct a stacked DLS image of each subfield in the R band, correcting for cosmic rays and saturated objects, fixing the astrometric calibration, and correcting the image shape and photometry for optical distortion. The uncertainty in the R-band magnitude is $\sim 0.05$ mag. We derive the galaxy catalog using SExtractor (Bertin & Arnouts 1996) on the final stacked images. We remove objects within the radius of the diffraction pattern around bright stars. The total area excluded around 778 stars is 0.215 deg$^2$ (5.4% of the survey).

The absolute magnitude $M_R$ calculation includes both $k$- and evolutional $e$- corrections. We use the $k+e$ correction determined by Annis (2001) using the Pegase code (Le Borgne & Rocca-Volmerage 2002). The $k+e$ correction requires classification as one of nine galaxy types (bright cluster galaxy, elliptical, S0, Sa, Sb, Sbc, Sc, Sd, and irregular). We classify the galaxies according to the SDSS $g-i$ color and galaxy redshift. We apply the SDSS r-band $k+e$ correction to the DLS R-band photometry because the shape of the filter bands are similar and the difference in corrections for the different bands is negligible. We estimate the uncertainty in the $k+e$ correction from the difference in the correction for adjacent galaxy types. The uncertainty ranges from a maximum of $\sim 0.02$ mag at $z = 0.08$ to 0.03–0.13 mag at $z = 0.38$, depending on the galaxy type.

There are 51 galaxies in our $z = 0.080$–0.376 sample with a Hectospec redshift but no SDSS photometry for galaxy classification and $k+e$ correction, including three galaxies in major pairs (Section 3.2). In 34 of the 51 cases, we use the DLS $(V-R)$ color to estimate the $(g-i)$ color for the $k+e$ correction. For the 17 cases where we lack both DLS $(V-R)$ and SDSS data (including two in major pairs), we assume the galaxy type is Sa. The $k+e$ correction for the galaxy type Sa is in the middle of the range for the different galaxy types; choosing a different $k+e$ correction has no significant effect on the results. At the redshift $z = 0.3$, the apparent $R = 20.3$ limit corresponds to a $k+e$ corrected absolute magnitude $M_R = -21.4$ for a typical late-type galaxy, and to $M_R = -21.8$ for a typical early-type galaxy.

### 2.3. Spectroscopic Measurements

The Hectospec spectrograph 270 line mm$^{-1}$ grating yields $\sim 6$ Å pixel$^{-1}$ dispersion over the wavelength range 3700–9300 Å (Fabricant et al. 2008). The 300 optical fibers with 1′′ diameter are placed radially within a 1″ diameter field. About 30 of the fibers measure sky background during each pointing.

We reduce Hectospec data with the standard Harvard-Smithsonian Center for Astrophysics Hectospec reduction pipeline$^5$ (Fabricant et al. 2005; Mink et al. 2007). We measure the galaxy redshift using the program RVSÅO (Kurtz & Mink 1998; Fabricant et al. 2005). The total rms internal error in the redshift is 34 km s$^{-1}$ for emission line galaxies and 65 km s$^{-1}$ for absorption line galaxies, based on repeat observations of 812 emission lines and 542 absorption line galaxies. We further process spectra to correct for atmospheric extinction and to remove the narrow absorption lines from H$_2$O and O$_2$ at wavelengths longer than $\sim 6000$ Å. We also correct for relative throughput as a function of wavelength (Fabricant et al. 2008).

We compute the emission line flux by integrating the counts in a fixed-width band in the rest frame centered on the central wavelength of the line; we subtract the continuum level. The spectral regions where we measure H$\alpha$ and H$\beta$ emission are 6562.8 ± 8 Å and 4861.3 ± 8 Å, respectively. We compute the continuum from the average of regions on either side of the band after rejecting noisy data. The rms scatter in the line flux is 23% for H$\alpha$, and internal systematic error in H$\alpha$ is $\sim 18\%$, based on duplicate observations of 592 galaxies.

The calibrated R-band photometry from the DLS in a 1′5 diameter aperture serves as reference for conversion of counts to flux in the 1′5 diameter fiber. This calibration process removes variation caused by seeing, clouds, telescope tracking and guiding, and astrometry and alignment errors for light losses that are wavelength independent (Fabricant et al. 2008).

Comparison of Hectospec spectra with a sample of overlapping SDSS spectra shows that the median ratio of the spectra is constant to $\sim 5\%$ over the range 3850–8000 Å, and the offsets in the ratios of the median H$\alpha$ flux and median rest-frame H$\alpha$ equivalent width (EW(H$\alpha$)) are $\sim 3\%$ (Fabricant et al. 2008).

We also compute the spectroscopic indicator $D_n4000$, a measure of the stellar population age, which is defined as the ratio of flux in the band 4000–4100 Å to flux in 3850–3950 Å (Balogh et al. 1999). The rms scatter in $D_n4000$ is 0.086. The internal systematic errors in $D_n4000$ are very small, 4.5%, based on repeat measurements of 1468 galaxies. The comparison of our measured $D_n4000$ with an overlapping sample of SDSS spectra shows a median ratio of 1.00 (Fabricant et al. 2008).

#### 2.3.1. H$\alpha$ Specific Star Formation Rate

We compute the SSFR$_{H\alpha}$ from the H$\alpha$ flux ($f_{H\alpha}$) normalized by the R-band 1′5 aperture magnitude. The H$\alpha$ flux must first be corrected for stellar absorption and for reddening.

To determine the stellar absorption at H$\alpha$ and H$\beta$, we fit the individual spectrum using the Tremonti et al. (2004) continuum subtraction method (see also Westra et al. 2010). This method fits the calibrated spectra with stellar population models to estimate the ages of the stellar populations within the galaxy. Like Tremonti et al., we assume that the star formation history of a galaxy can be represented as the sum of discrete bursts of star formation, and we fit for the burst ages.

Figure 1 illustrates the fit of the contributions from the different starburst populations in an example galaxy spectrum. The template spectra that we use are Bruzual & Charlot (2003) stellar population models. The models include ten different ages of bursts (0.005, 0.025, 0.1, 0.3, 0.6, 0.9, 1.4, 2.5, 5, and 10 Gyr) at solar metallicity. We also add reddening as an additional parameter using the Charlot & Fall (2000) attenuation model. Finally, we match the models in redshift, pixel size, and spectral resolution to each galaxy spectrum. The core of the code adapted from Tremonti et al. uses the IDL mpfitfun routine from the Markwardt library (Markwardt 2009) to find the best-fitting combination of models.

The absorption-corrected H$\alpha$ flux is

$$f_{c,H\alpha} = f_{H\alpha} \left( \frac{EW(H\alpha) + EW_{Abs}}{EW(H\alpha)} \right),$$

and similarly for $f_{c,H\beta}$. The ratio of $f_{c}/f$ is equivalent to $EW_{c}/EW$. All EW and line fluxes of H$\alpha$ or H$\beta$ in this paper are absorption corrected.

We correct the H$\alpha$ flux for reddening according to the standard method (Calzetti et al. 2000). We compute the wavelength-dependent extinction, $A_{\lambda}$, where the factors $k(H\alpha) = 3.326$ and $k(H\beta) = 4.598$ give the differential extinction between the wavelengths of H$\alpha$ and H$\beta$ for the case of a starburst

---

5 http://tdc-www.harvard.edu/instruments/fectospec/reduce.html
galaxy \(k(V) = 4.05\); Calzetti et al. 2000). The parameter \(R_{\text{ap}}\) relates the observed to intrinsic Balmer decrement (2.87; Calzetti 2001).

We correct for reddening using average \(E(B - V)\) values for bins of absolute luminosity and redshift. This procedure mitigates the effects of noisy individual \(H\beta\) measurements, which contribute significant noise to the \(E(B - V)\) values. Figure 2 shows the EW(H\(\alpha\)) versus Balmer decrement for individual galaxies. A population of galaxies with EW(H\(\alpha\)) \(< 20\) Å and Balmer decrement \(> 10\) result from noisy \(H\beta\) measurements. The total internal error in EW(H\(\alpha\)) is 18% and the error in the Balmer decrement is 25%. We determine the Balmer decrement for each luminosity and redshift bin from the median value in the appropriate bin derived from the 484 galaxies with signal-to-noise ratio, \(S/N \geq 3\) in \(H\alpha\), \(S/N \geq 2\) in \(H\beta\), EW(H\(\alpha\)) \(> 3\) Å, EW(H\(\beta\)) \(> 2\) Å, \(D_r 4000 \leq 1.44\), and classified as star forming (Section 4.1). Using the median \(E(B - V)\) value eliminates huge and unphysical reddening correction factors for individual galaxies.

Once we correct the \(H\alpha\) flux for stellar absorption and for reddening, we calculate the \(H\alpha\) luminosity \(L_{H\alpha}\) using the luminosity distance. We convert from \(L_{H\alpha}\) to SFR using the conversion factor of Kennicutt (1998):

\[
\text{SFR}_{H\alpha}(M_{\sun} \text{yr}^{-1}) = \frac{L_{H\alpha}}{1.27 \times 10^{41} \text{ erg s}^{-1}}. \tag{2}
\]

We normalize the \(H\alpha\) SFR by the galaxy \(R\)-band aperture magnitude to compute the SSFR\(H\alpha\). We use the 1.5” Hectospec aperture covering fraction as a function of galaxy luminosity and redshift. Most galaxies in the sample have a covering fraction \(> 20\%\); Figure 3 shows the fraction of galaxies with covering fraction \(> 20\%\) as a function of redshift for the galaxies (both paired and unpaired) at \(z = 0.080-0.376\).

Fabricant et al. (2008) conducted a detailed investigation of aperture effects in their sample of overlapping Hectospec and SDSS spectra, a subset of our full spectroscopic survey. SDSS spectra are acquired through a 3” aperture. Thus, Fabricant et al. scaled the Hectospec line fluxes by the 3” aperture \(R\)-band magnitude to make direct comparisons with the SDSS line fluxes. They conclude that the median [O ii] 3727 Å and \(H\alpha\) line fluxes from Hectospec agree to within 3%–4% of the SDSS values, and that the scatter in the line fluxes is dominated by systematic uncertainties. The 3%–4% difference between Hectospec and SDSS line flux measurements is small compared to the 23% rms scatter in the \(H\alpha\) line flux from Hectospec.

The agreement between the Hectospec and SDSS data implies that the \(H\alpha\) SFR within apertures of 1.5” and 3” scale with the \(R\)-band galaxy luminosity. The relative agreement between the scaled Hectospec and SDSS \(H\alpha\) line flux is independent of the absolute magnitude (see Figure 13 in Fabricant et al. 2008), apparent magnitude, redshift, and 25% light radius of the galaxies. Westra et al. (2010) similarly found that the \(H\alpha\) luminosity determined from the 1.5” fiber and \(R\)-band magnitude is consistent with the \(H\alpha\) luminosity from the 3” aperture photometry and \(R\)-band magnitude of Shioya et al. (2008).
Like the Hα luminosity, we assume that $D_n4000$ observed in the 1′5 aperture represents the galaxy as a whole. Fabricant et al. (2008) showed that the Hectospec and SDSS measurement of $D_n4000$ agree very well over the scales observed (1.4–2.8 kpc radius at $z = 0.1$). This agreement again suggests that measurement of $D_n4000$ for the stellar population included in the Hectospec aperture is not significantly affected by systematic biases compared to the population observed in the larger SDSS aperture.

3. PAIR AND FIELD SAMPLE SELECTION

We measure the effects of galaxy interactions on the star formation activity and other galaxy properties at intermediate redshift. We use two pair samples derived from the 6935 galaxies with spectroscopy and $R < 20.3$ in the redshift range $z = 0.080–0.376$.

The first sample, the “full” major pairs sample, includes all galaxies in major pairs that meet our projected spatial and line-of-sight peculiar velocity criteria (Section 3.1) in the range $z = 0.080–0.376$. There are 622 galaxies in the full major pairs sample.

The second sample, the “volume-limited” major pairs sample, is a subset of the full major pairs sample, and is restricted to galaxies that meet both redshift and absolute luminosity selection criteria (Section 3.2). The volume-limited major pairs sample allows us to study the strength, frequency, and timescale of triggered star formation. The volume-limited major pairs sample is well suited to comparison with the predictions of the numerical simulations of Di Matteo et al. (2008), who measure the intensity, frequency, and duration of merger-driven star formation in their large suites of numerical simulations of major interactions. The volume-limited major pairs sample contains 339 galaxies.

Our pair samples are the largest spectroscopic samples of pairs to date at intermediate redshift ($z \approx 0.1 – 0.4$). In comparison, the Millennium Galaxy Catalog (MGC; Liske et al. 2003; Driver et al. 2005; Allen et al. 2006) is a 96% complete spectroscopic survey of 10,095 galaxies to $B_{MGC} < 20$ mag. The MGC is similar in number and completeness to our sample but is at lower redshift. De Propris et al. (2007) study pair galaxies in the MGC; they identify a volume-limited sample of 3237 galaxies in the range $0.010 < z < 0.123$, including 112 galaxies in pairs with projected separation $\Delta D < 28$ kpc [$20 h^{-1}_{100}$ kpc]. The CNOC2 Redshift Survey contains redshifts for $\sim 5000$ galaxies at $0.1 < z < 0.6$ with a cumulative completeness of 50% and differential completeness of 20% at the limit $R_c \leq 21.5$ (Yee et al. 2000; Patton et al. 2002). Patton et al. (2005) studied properties of dynamically close pairs in the CNOC2 survey. Our sample covers the same redshift range but is substantially more complete than CNOC2. Table 1 lists the selection criteria and the number of galaxies in the full major pair sample and in the volume-limited major pair sample.

3.1. Full Major Pairs Sample

We select galaxy pairs with projected spatial separation $\Delta D \leq 70$ kpc, corresponding to the limit $\Delta D \leq 50 h_{100}$ kpc commonly applied in previous studies (e.g., Barton et al. 2000). We require a line-of-sight peculiar velocity difference $\Delta V/(1 + z) < 500$ km s$^{-1}$. The limit of $\Delta D \leq 70$ kpc includes pair galaxies with the most significantly enhanced EW(Hα) (e.g., Barton et al. 2000), while minimizing the presence of interlopers. The $\Delta V$ limit is motivated by Barton et al. (2000), who find no significantly enhanced EW(Hα) emission in pairs with $\Delta V \geq 500$ km s$^{-1}$ (their Figure 2(b)) in their sample of 786 galaxies from the CfA2 Redshift Survey, and is consistent with previous pair studies (De Propris et al. 2007; Woods et al. 2006).

We exclude potential pair galaxies from our sample if either member of the pair lies within a projected 70 kpc from the survey boundary or the edge of the region excluded around a bright star. For galaxies in a compact group, we compare each galaxy to its nearest neighbor; odd numbers of “pair” galaxies can occur in compact groups.

We compute the total pair fraction for all pairs—major and minor—in the redshift interval $z = 0.080–0.376$. There are 809 galaxies in major or minor pairs or compact groups that meet the projected spatial and peculiar velocity requirements. The total pair fraction is 12% (809/6935).

We restrict our sample to major pairs with $|\Delta M_K| < 1.75$, corresponding to a luminosity (approximate mass) ratio $> 1/5$. Simulations of interacting galaxies predict that major interactions are more effective than minor interactions at triggering star formation; only the fainter companion in a minor interaction occasionally shows triggered star formation (Cox et al. 2008). Observations of major and minor pair galaxies support this predicted behavior (Dasyra et al. 2006; Woods & Geller 2007; Ellison et al. 2008; Westra et al. 2010). The full major pair sample includes 622 galaxies in major pairs in the range $z = 0.080–0.376$. Figure 4 shows the redshift distribution and Figure 5 shows the distribution of projected separation for the full major pairs sample. Table 2 lists the full major pair sample galaxies and their properties.
Table 2
Sample of Major Galaxy Pairs

| Pair | R.A. | Decl. | z   | m_R | M_R | ΔD (kpc) | ΔV (km s^-1) | D_n | SSFR_Hα (M_☉ yr^-1 / 10^{10} M_☉) |
|------|------|-------|-----|-----|------|----------|--------------|-----|----------------------------------|
| 001  | 9:14:52.622 | 30:05:40.858 | 0.26472 | 19.56 | -21.23 | 68 | 388 | 1.29 | 1.36 |
| 001  | 9:14:53.920 | 30:05:40.377 | 0.26309 | 19.97 | -20.76 | 68 | 388 | 1.79 | 0.10 |
| 002  | 9:14:52.849 | 30:17:05.567 | 0.12805 | 20.10 | -18.80 | 50 | 51 | 0.96 | 1.26 |
| 002  | 9:14:53.528 | 30:17:25.933 | 0.12813 | 19.97 | -19.74 | 50 | 51 | 1.05 | 3.99 |
| 003  | 9:14:53.583 | 30:31:44.906 | 0.25643 | 20.20 | -20.40 | 65 | 108 | 1.14 | 1.18 |
| 003  | 9:14:54.188 | 30:31:30.369 | 0.25688 | 19.60 | -21.14 | 65 | 108 | 0.00 | 0.04 |
| 004  | 9:14:57.683 | 29:57:15.864 | 0.24721 | 19.08 | -21.44 | 26 | 133 | 1.07 | 3.83 |
| 004  | 9:14:58.198 | 29:57:15.988 | 0.24780 | 19.21 | -21.34 | 26 | 133 | 1.11 | 3.79 |
| 005  | 9:14:57.762 | 29:49:34.947 | 0.18074 | 18.58 | -21.20 | 26 | 171 | 1.44 | 0.36 |
| 005  | 9:14:58.434 | 29:49:34.583 | 0.18014 | 18.81 | -22.01 | 26 | 171 | 1.73 | 0.00 |

Notes.

a Standard ΛCDM cosmology: H_0 = 71 km s^-1 Mpc^-1, Ω_m = 0.3, and Ω_Λ = 0.7.
b J2000 coordinates.
c Typical error estimates: cz:3 4k ms^-1 emission line galaxies, 65 km s^-1 absorption line galaxies (Section 2.3), m_R:0.05 mag (Section 2.2), D_n4000:4.5%. (Section 2.3), M_R:∼0.1 mag, varies with redshift and galaxy type (Section 2.2), SSFR_Hα:30% (Section 2.3.1).
d k-c corrected.

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

Visible evidence of tidal interactions in the DLS combined BVR-band images, such as tidal tails, marked asymmetries, or extended halos, can be seen in ~1/4 of the major pair galaxies. Analyzing the morphological features in detail is beyond the scope of this project. The images are available on our Web site (see footnote 4).

3.2. Volume-limited Major Pairs Sample

We construct a volume-limited sample of major galaxy pairs to study trends in triggered star formation and other galaxy properties. The volume-limited sample contains galaxies in the redshift range 0.080 < z < 0.310 and with magnitude M_R < -20.8. The limits on M_R and z maximize the number of galaxy pairs in the volume-limited sample. The lower redshift limit, z = 0.080, minimizes aperture effects (Section 2.3.2). There are 339 galaxies in major pairs in the volume-limited sample.

The distribution of projected separations (Figure 5) is relatively flat from 15 < ΔD < 70 kpc, as expected from the galaxy correlation function (e.g., Estrada et al. 2008). At separations <15 kpc, galaxies in the DLS images may not be resolved into separate systems. Figures 6 shows the distribution of absolute magnitudes of galaxies in the full major pair sample and in the volume-limited major pair sample.

3.2.1. Volume-limited Unpaired Field Sample

We construct a volume-limited sample of galaxies with no detected companions (the “field” sample) for comparison with the volume-limited pair sample. The field sample includes only galaxies without companions that satisfy the pair selection criteria. The field galaxies in the volume-limited sample meet the same magnitude (M_R < -20.8) and redshift criteria as the major pair galaxies. The range of magnitude differences excluded from the field galaxies (|ΔM_R| < 2) is slightly broader than the range accepted for major pairs (|ΔM_R| < 1.75) to exclude systems that could marginally be considered major pairs. We exclude galaxies within 70 kpc from...
2220 field galaxies (74%) in the range 18 ≤ mR < 20, companions fainter by up to 1.75 mag. There are 1633 out of the fraction of galaxies in pairs in the volume-limited sample and galaxies likely to have an undetected major companion. The volume-limited field sample includes 2234 galaxies. The distributions of M_R in the volume-limited major pair sample and volume-limited field sample are similar. We use the Kolmogorov–Smirnov (K-S) test to determine that the two distributions are drawn from the sample parent sample (P_K-S = 0.37). The volume-limited major pair sample and the unpaired field sample also have similar distributions of redshifts (P_K-S = 0.29). Figure 7 shows the redshift distribution of field galaxies.

Some of the field galaxies may have a major companion fainter than the survey limit. We estimate the fraction of field galaxies likely to have an undetected major companion. The fraction of galaxies in pairs in the volume-limited sample and with apparent magnitude m_R < 18.55 is 11% (102/902). The m_R < 18.55 limit allows identification of pair galaxies with companions fainter by up to 1.75 mag. There are 1633 out of 2220 field galaxies (74%) in the range 18.55 < m_R < 20.3 that could have a major companion fainter than our survey limit. An additional factor of 0.5 accounts for a pair galaxy having a 50% probability of being brighter than its companion. Hence, the fraction of field galaxies likely to have an undetected major companion is ∼4%. There are also some field galaxies in later stages of merging such that a companion is unresolved. Because the field sample contains some pairs and merger remnants, any differences in galaxy properties between the pairs and field samples attributable to interactions are lower limits.

the survey boundary or 70 kpc from the boundaries around bright stars. The volume-limited field sample includes 2234 galaxies.

The distributions of M_R in the volume-limited major pair sample and volume-limited field sample are similar. We use the Kolmogorov–Smirnov (K-S) test to determine that the two distributions are drawn from the sample parent sample (P_K-S = 0.37). The volume-limited major pair sample and the unpaired field sample also have similar distributions of redshifts (P_K-S = 0.29). Figure 7 shows the redshift distribution of field galaxies.

Some of the field galaxies may have a major companion fainter than the survey limit. We estimate the fraction of field galaxies likely to have an undetected major companion. The fraction of galaxies in pairs in the volume-limited sample and with apparent magnitude m_R < 18.55 is 11% (102/902). The m_R < 18.55 limit allows identification of pair galaxies with companions fainter by up to 1.75 mag. There are 1633 out of 2220 field galaxies (74%) in the range 18.55 < m_R < 20.3 that could have a major companion fainter than our survey limit. An additional factor of 0.5 accounts for a pair galaxy having a 50% probability of being brighter than its companion. Hence, the fraction of field galaxies likely to have an undetected major companion is ∼4%. There are also some field galaxies in later stages of merging such that a companion is unresolved. Because the field sample contains some pairs and merger remnants, any differences in galaxy properties between the pairs and field samples attributable to interactions are lower limits.

4. SPECTROSCOPIC IDENTIFIERS

In this section, we describe galaxy classification metrics to identify candidates for tidally triggered star formation. We identify the galaxies with strong AGNs to remove them from our sample of star-forming galaxies (Section 4.1). We describe the use of the spectroscopic indicator D_4000 as a galaxy classification tool (Section 4.2).

4.1. Identification of AGNs

We exclude strong AGNs from our analysis because measurements of emission lines, such as Hα, would not accurately represent star formation activity in galaxies with active nuclei. We distinguish narrow-line AGNs from star-forming galaxies with measurements of the emission lines Hα, Hβ, [N ii], and [O iii] using the classification metric of Kewley et al. (2006), based on the “BPT” diagrams of Baldwin et al. (1981). The line fluxes Hα and Hβ are stellar absorption corrected.

The requirements we place on the spectra for classification are very mild: EW(Hα) > 2 Å and EW(Hβ) > 2 Å. We impose no requirement on [N ii] or [O iii] because galaxies without measurable [N ii] or [O iii] could only have a very weak AGN. Furthermore, galaxies with EW(Hα) < 2 Å have minimal star formation. Figure 8 shows the classification diagram for the pair galaxies.

We include composite galaxies in our pair and field samples, but exclude the galaxies classified as AGNs. Although these criteria may admit weak AGNs, most of the contribution to the Hα emission should be from star-forming regions. There are 119 narrow-line AGNs in the z = 0.080–0.376 sample, 19 of which are in major pairs (Section 3.2).

Our ability to detect narrow-line AGNs within the host galaxy declines with redshift because the covering fraction of the spectroscopic fiber increases with redshift. At redshift z = 0.080, the 1.7 fiber diameter corresponds to 2.2 kpc, and at z = 0.310, the 1.5 fiber covers 6.8 kpc. We also admit fewer AGNs at higher redshift into our spectroscopic sample because objects with stellar light profiles are excluded from our spectroscopic catalog.

Despite these caveats to our ability to detect narrow-line AGNs at higher redshift, the mean redshift of the narrow-line AGNs in the full spectroscopic sample (both pair and unpaired galaxies) is higher than that of the objects classified
as star forming or composite: mean $z = 0.27$ and $z = 0.23$, respectively. The redshift distributions differ significantly ($P_{KS} = 1.6 \times 10^{-5}$). We attribute this trend to the evolutionary decline in AGN activity at low redshift (e.g., Brand et al. 2005; Cavaliere 2000).

We identify galaxies with broad emission lines by visually inspecting all spectra that are potential broadened line objects. The criteria for broad-line AGN candidates are $\text{EW(H}\alpha) > 3\, \AA$ and the line flux in a band widened from $\pm 8\, \AA$ to $\pm 12\, \AA$ increases the measured $\text{H}\alpha$ flux by more than 10%, or $\text{EW([N\,II])} > 3\, \AA$ and the line flux in a band widened from $\pm 8\, \AA$ to $\pm 12\, \AA$ increases the measured $\text{[N\,II]}$ flux by more than 10%. We identify 26 galaxies with broadened lines in the $z = 0.080-0.376$ sample. Five of these are in major pairs.

We exclude galaxies classified as AGNs from our analysis of star formation activity; we retain the non-AGN companion. Table 3 reports the AGN fraction in each pair sample and in the matching unpaired field sample. The AGN fraction in pairs exceeds that in the matching field sample for each of the subsamples. The increase in AGN fraction for both the full and volume-limited major pair samples is a factor of $\sim 2$, a significance of $\sim 2\sigma$. The higher AGN fractions in the volume-limited samples (pair and field) compared to the full samples are consistent with the exclusion of lower luminosity galaxies from the volume-limited sample, which are less likely to contain an AGN.

4.2. Galaxy Classification by $D_{n}\alpha4000$

It is useful to segregate galaxies into two categories: early-type galaxies, which are generally gas-poor and have little or no active star formation, and late-type, which contain more gas and have young stellar populations. The gas-rich systems are potentially susceptible to tidally triggered star formation in major interactions (e.g., Mihos & Hernquist 1996; Tissera et al. 2002; Cox et al. 2006; Di Matteo et al. 2007). Interactions between gas-poor galaxies (“dry mergers”) produce little or no star formation activity, although they contribute substantially to the build-up of massive galaxies (e.g., Tran et al. 2005; Van Dokkum 2005; Cattaneo et al. 2008). Our analysis of star formation activity in pair galaxies focuses on the late-type systems.

There are a number of classification schemes to separate the early- and late-type galaxy populations. Photometric discriminants include color, concentration, and absolute magnitude (e.g., Strateva et al. 2001), and spectroscopic methods include $D_{n}\alpha4000$ and $\text{H}\delta$ absorption (Kauffmann et al. 2003). The $D_{n}\alpha4000$ indicator discriminates by stellar population age. At wavelengths bluer than $4000\, \AA$, metal lines in low mass stars absorb the light and cause a “break” in the spectrum. As the stellar population ages and the massive, hot stars die off, $D_{n}\alpha4000$ increases monotonically with time. Kauffmann et al. (2003) used stellar population models to show that galaxies with $D_{n}\alpha4000 \lesssim 1.5$ have young stellar populations ($\lesssim 1$ Gyr). Metallicity has a strong effect on the value of $D_{n}\alpha4000$ only after 1 Gyr past a burst of star formation (see Figure 2 in Kauffmann et al. 2003). Measurement of $D_{n}\alpha4000$ is insensitive to galaxy reddening.

Vergani et al. (2008) used $D_{n}\alpha4000$ to separate spectroscopic early-type galaxies from late-type galaxies at a dividing line of $D_{n}\alpha4000 = 1.5$ in their analysis of galaxy stellar mass assembly in the VIMOS VLT Deep Survey. Mignoli et al. (2005) also used $D4000 = 1.6$ as a dividing line (different definition of $D4000$ from Bruzual 1983: ratio of flux in bands 4050–4250 Å to 3750–3950 Å) along with other spectral measurements to classify galaxies in the K20 survey, a near-IR selected redshift survey. We follow this approach.

The distribution of $D_{n}\alpha4000$ is bimodal, separating galaxy populations dominated by old stars from systems with recent star formation. Figure 9 shows the distribution of $D_{n}\alpha4000$ for the 6644 galaxies (both pair and unpaired) at $z = 0.080-0.376$ with a robust $D_{n}\alpha4000$ measurement. The peaks are at $\sim 1.15$ and $\sim 1.75$. Kauffmann et al. (2003) similarly observed a bimodal distribution in $D_{n}\alpha4000$, with peaks at 1.30 and 1.85 in their sample of $\sim 100,000$ galaxies in the SDSS. We choose the minimum between the bimodal distribution as our dividing line, $D_{n}\alpha4000 = 1.44$ (Figure 9). We refer to galaxies with $D_{n}\alpha4000 \leq 1.44$ as “low” $D_{n}\alpha4000$ galaxies and those with $D_{n}\alpha4000 > 1.44$ as “high” $D_{n}\alpha4000$ galaxies. Our analysis of star formation activity includes the low $D_{n}\alpha4000$ galaxy in a mixed pair, but does not require both galaxies to have $D_{n}\alpha4000 < 1.44$.

The emission line fraction is a strong function of $D_{n}\alpha4000$. Figure 10 shows the steep decline in the fraction of emission line galaxies between $D_{n}\alpha4000 = 1.3$ and 1.5. The emission line galaxies have $\text{EW(H}\alpha) \gtrsim 3$ or $\text{EW([O\,II])} \gtrsim 3$. Thus segregating by $D_{n}\alpha4000$ is reasonable and corresponds well to segregating by the presence of emission lines.

We also compare the use of $D_{n}\alpha4000$ for galaxy classification with color, another widely used indicator of galaxy type. Figure 11 shows the bimodal distribution of rest-frame SDSS ($g-r$) color versus $D_{n}\alpha4000$. We compute the rest-frame SDSS ($g-r$) color using the $k+c$ correction determined by Annis (2001) from the Pegase code (Le Borgne & Rocca-Volmerage 2002). The separation by $D_{n}\alpha4000$ is more sharply defined than that of rest-frame color. The rest-frame galaxy colors are affected by reddening and depend on the noisy $k+c$ corrections. $D_{n}\alpha4000$

| Table 3 | AGN Fraction |
|---------|--------------|
| Sample  | Pair$^a$     | Field$^b$ | Significance | Pair Sample Size |
| Full    | 8 ± 2%       | 4 ± 2%    | 2$\sigma$   | 280             |
| Volume limited | 12 ± 3%      | 5 ± 2%    | 2$\sigma$   | 128             |

Notes.

$^a$ Fraction of AGNs compared to fraction of galaxies that meet our criteria for classification (Section 4.1). We identify only very bright AGNs with our spectra and our classification criteria.

$^b$ Proportional representation of field galaxies matching the $M_\star$ and redshift distribution of the pair sample.

Figure 9. Distribution of $D_{n}\alpha4000$ for all galaxies in the spectroscopic sample. The bimodal distribution has a local minimum at $D_{n}\alpha4000 = 1.44$ (dashed line).
Figure 10. Fraction of emission-line galaxies as a function of $D_n4000$ for all galaxies in the spectroscopic sample, excluding AGNs. Emission line galaxies have $\text{EW}(\text{H}\alpha) \geq 3$ or $\text{EW}(\text{[O\ II]}) \geq 3$. There is a steep decline in the fraction between $D_n4000 = 1.3$ and $1.5$. Error bars from bootstrap resampling indicate the 95% confidence intervals.

Figure 11. $D_n4000$ vs. rest-frame ($g-r$) color. Two galaxy populations are visible: systems with blue colors (lower left) and systems with red colors (upper right). The dashed line indicates $D_n4000 = 1.44$ (see Figure 9).

provides a well-defined method to segregate galaxies and has the advantage that no redshift-dependent corrections are required.

5. LOCAL DENSITY EFFECTS

Because pair galaxies are more common in higher density regions (Barton et al. 2007), and because cluster and group galaxies are more likely to be red with less active star formation than isolated galaxies (e.g., Hubble & Humason 1931; Cooper et al. 2007; Gerke et al. 2007), comparisons between pair and field populations without attention to density can strongly bias the interpretation of studies of close pairs. Barton et al. (2007) emphasize that including high density regions suppresses the detection of triggered star formation.

To compare the environment of pair and field galaxies, we compute the number of companions ($N_c$) within a comoving sphere of radius 985 kpc centered on the galaxy (radius equivalent to $700 h_{100}^{-1}$ kpc). The 985 kpc radius is within the typical virial radius of clusters ($\sim 1 h_{100}^{-1}$ Mpc; Rines et al. 2003), and maximizes the survey area included in our analysis. This density measurement is consistent with that of Barton et al. (2007). We measure $N_c$ within the volume-limited sample, requiring that the galaxy reside within $z = 0.080-0.310$ and have magnitude $M_R < -20.8$. We count all neighboring galaxies, not just major companions. We exclude regions within 985 kpc of the survey edge.

Barton et al. (2007) predicted that most observed pair galaxies reside in higher mass cluster or group-sized halos, whereas field galaxies are usually in isolated low mass halos. We test this prediction with our complete volume-limited data set, using $N_c$ as a proxy for halo membership. Note that our $N_c$ counts neighbors; the halo count $N$ in Barton et al. counts total halo occupation, i.e., $N = N_c + 1$.

Figure 12 shows the fraction of galaxies with various $N_c$ as a function of projected distance to the nearest neighbor. Pair galaxies fall in the range $\Delta D < 70$ kpc. As Barton et al. show, pairs occur more frequently in locally dense regions. We find that 32% of pair galaxies have $N_c \geq 8$. The overall fraction of galaxies in dense regions is smaller: 19% of all galaxies lie in regions with $N_c \geq 8$.

Our observations are in excellent agreement with the predictions of Barton et al. (2007). They find that 39% of pair galaxies are in a host halo with total number of galaxies $N \geq 9$; 19% of galaxies in the sample as a whole have $N \geq 9$ ($N_c \geq 8$). Selecting a sample of field galaxies for a fair comparison of SSFRs thus necessitates consideration of local density effects.

Selecting star-forming galaxies with young stellar populations (low $D_n4000$) already reduces the effects of the environment because young, blue galaxies are relatively more abundant...
in low density regions. In the volume-limited major pair sample, 63% of the low $D_n 4000$ non-AGN galaxies reside in regions with $N_c \leq 4$.

Restricting the analysis of star formation activity solely by $D_n 4000$ does not, however, eliminate differences in star formation activity with local density. The distribution of local densities differs between low $D_n 4000$ pair and field galaxies ($P_{KS} = 1.6 \times 10^{-5}$). Thus, we restrict any direct comparisons of specific star formation activity in pairs and field galaxies to low density regions to ensure that density effects do not dominate our measurements of star formation activity. A moderate limit of $N_c \leq 4$ maximizes our sample size.

6. MEASUREMENTS OF TIDALLY TRIGGERED STAR FORMATION

Here we quantify the frequency, strength, and timescale of the triggered star formation for galaxies at intermediate redshift. We examine trends in star formation activity across redshift and luminosity for the galaxies in the volume-limited sample. The completeness and quality of spectrophotometry enable us to carry out the most detailed spectroscopic analysis of pair galaxies to date in the redshift range $z = 0.080-0.376$. We examine the SSFR$_{H\alpha}$ (Section 2.3.1), the spectroscopic parameter $D_n 4000$ (Section 4.2), and a set of stellar population models (Section 2.3.1).

The volume-limited pair sample is well suited to comparison with the predictions of numerical simulations. We compare our observations with the predictions of Di Matteo et al. (2008), who measured the intensity, frequency, and duration of merger-driven star formation in their large suites of numerical simulations of major interactions.

6.1. Star Formation Indicators and Projected Separation

We examine a set of star formation indicators as a function of projected separation to look for the signature of triggered star formation at redshifts $0.080-0.376$. The star formation–$\Delta D$ anti-correlation frequently observed at low redshift (Barton et al. 2000; Lambas et al. 2003; Nikolic et al. 2004; Woods et al. 2006; Geller et al. 2006; Woods & Geller 2007; Li et al. 2008; Ellison et al. 2008) results from an increase in central star formation activity triggered by a close pass from a neighboring galaxy. As the pair galaxies move apart and the burst ages, the star formation activity decreases.

We observe a strong anti-correlation between SSFR$_{H\alpha}$ and $\Delta D$ in the sample of all low $D_n 4000$ major pair galaxies at $z = 0.080-0.376$ (at all local densities). The Spearman-rank test computes a probability of no correlation of $P_{SR} = 6.0 \times 10^{-4}$ for the 134 galaxies in the sample (Figure 13, top left panel.) The range of absolute luminosities and local densities in this sample corresponds to that included in typical samples at low redshift (e.g., Barton et al. 2000). The range of absolute luminosities and local densities in this sample corresponds to that included in typical samples at low redshift (e.g., Barton et al. 2000).

Figure 13 shows the mean SSFR$_{H\alpha}$ as a function of $\Delta D$ for low $D_n 4000$ galaxies in low density regions in the volume-limited major pairs sample (top right panel). We measure a correlation between SSFR$_{H\alpha}$ and $\Delta D$ for the 70 galaxies in this sample, where $P_{SR} = 1.3 \times 10^{-2}$. The decreased significance compared
to the sample of all major pair galaxies results from the reduction in sample size. Excluding the lowest luminosity galaxies from the volume-limited sample may also reduce the signal of the interaction because low luminosity galaxies are more strongly affected than the more luminous galaxies.

We measure a weak correlation between $\Delta D$ and $D_n4000$ for the low $D_n4000$ galaxies in the volume-limited pair sample at the level of $P_{\text{SR}} = 5.1 \times 10^{-2}$; bursts with small $\Delta D$ have small $D_n4000$ (Figure 13, bottom left panel). This trend is consistent with the expectation that close pairs have had the most recent starbursts, and hence harbor the youngest stellar populations.

We apply another measure of the recent star formation based on the stellar population models. The model-determined fraction of total luminosity at 5500 Å from the youngest discrete starburst population age (5 Myr) correlates with $\Delta D$ for the volume-limited major pair sample; $P_{\text{SR}} = 1.4 \times 10^{-2}$. Pairs at the smallest $\Delta D$ have the highest fractional contribution from a 5 Myr stellar population, compared to galaxies with larger $\Delta D$ (Figure 13, bottom right panel).

These results are consistent with other recent observations. At redshifts of $0.1 < z < 1.1$, Lin et al. (2007) likewise observed an anti-correlation between the median infrared luminosity of merging galaxies and pair separation in their sample of ~100 systems with data from the DEEP2 Galaxy Redshift Survey and Hubble Space Telescope/Advanced Camera for Surveys imaging. de Ravel et al. (2009) similarly found that the galaxy pairs at the smallest separations have the greatest median EW(O III) in their sample of 251 pairs in the VIMOS VLTI Deep Survey (Le Fèvre et al. 2005), which has a mean of redshift of $z = 0.76$.

We next explore properties of the galaxies that drive the correlation between star formation indicators and $\Delta D$—the galaxies with significant star formation rates at small separation. The galaxies with $\Delta D < 25$ kpc and SSFR$_{H\alpha} > 4 M_\odot$ yr$^{-1}/10^{10} M_\odot$ have luminosities similar to the rest of the low $D_n4000$ galaxies in the volume-limited sample ($M_R \approx -21.4$). These galaxies are bright; $M_R^b \approx -22.1$ for all galaxies in our spectroscopic sample in this redshift range (A. Diaferio et al. 2010, in preparation). The correlation between SSFR$_{H\alpha}$ and $\Delta D$ for luminous galaxies at redshifts $z = 0.1–0.3$ is an interesting observation for comparison with lower redshift results.

In the low redshift CfA2 Redshift survey, the lower mass galaxies (measured by rotation velocities) exhibit a anti-correlation between EW(Hα) and $\Delta D$; more massive galaxies do not (Barton 1999). They conclude that the least massive galaxies exhibit the strongest bursts of star formation and are responsible for driving their observed EW(Hα)–$\Delta D$ correlation. Both Woods & Geller (2007) and Ellison et al. (2008) found that at low redshift low mass luminosity galaxies exhibit relatively more powerful triggered specific star formation than high mass galaxies.

Finding luminous galaxies with strong evidence of triggered star formation at intermediate redshift is consistent with “downdizing” (Cowie et al. 1996), which suggests that higher mass (luminosity) galaxies formed their stars earlier, and that the lower mass galaxies have more efficient star formation at late times than the higher mass galaxies (Guzman et al. 1997; Brinchmann & Ellis 2000; Kodama et al. 2004; Bell et al. 2005; Juneau et al. 2005; Noeske et al. 2007).

### 6.2. Frequency and Strength of Triggered Star Formation

Gravitational interactions clearly trigger star formation in some cases (see references in Section 1). Some galaxies fail to have enhanced star formation because the pairs have not yet reached perigalacticon, the pairs may be mere interlopers along the line of sight, or they may have internal structure less conducive to gaseous inflows (Mihos & Hernquist 1996).

We place limits on the frequency of triggered star formation by comparing the SSFR$_{H\alpha}$ of the low $D_n4000$ pair galaxies with those of the low $D_n4000$ unpaired field galaxies in the volume-limited samples. Figure 14 shows the normalized distributions of SSFR$_{H\alpha}$ for the low $D_n4000$ galaxies in major pairs and the unpaired field galaxies. The dotted line indicates the median SSFR$_{H\alpha}$ for the field galaxies. Table 4 lists the quartiles of the distribution and the fraction of pair galaxies with SSFR$_{H\alpha}$ more than twice the field median. The results for the very close pairs, $\Delta D < 25$ kpc, are listed separately.

Table 4 shows that the low $D_n4000$ major pair galaxies have an excess of high SSFR$_{H\alpha}$ compared to the low $D_n4000$ field galaxies. We define the fraction of pair galaxies experiencing enhanced specific star formation as SSFR$_{H\alpha} = 2 \times F_{50}$, where $F_{50}$ is the median SSFR$_{H\alpha}$ for the field galaxies. According to this definition, $32 \pm 7\%$ of major pair galaxies experience enhanced specific star formation. A greater fraction of close pairs with $\Delta D < 25$ kpc, exhibit enhanced SSFRs: $42 \pm 13\%$. Observing a greater fraction of close pairs with enhanced star formation is consistent with triggering at the closest approach and the subsequent decline as the burst ages and the pair moves apart. We find only one galaxy with SSFR$_{H\alpha} > 5 \times F_{50}$.

A number of generic selection issues affect the measured frequency and strength of triggered star formation. The first issue is that a small fraction ($< 4\%$) of the field galaxies is likely to be in a pair with an undetected companion (Section 3.2.1). Second, excluding galaxies with strong AGN preferentially excludes pairs with active star formation because triggered AGN activity and star formation activity often occur as part of the same process (e.g., Hopkins et al. 2008). Third, we are unable to resolve some pairs or mergers at separations $\Delta D < 15$ kpc, where the strongest star formation enhancement is expected (e.g., Barton et al. 2000). Our measurement of the frequency and strength of triggered star formation should therefore be interpreted as lower limits.

We compare measurement of the frequency of triggered star formation from our volume-limited major pairs sample with the predictions of Di Matteo et al. (2008), who used numerical simulations to study the frequency, intensity, and duration of triggered star formation activity. Between 25% and 50% of their “fly-bys” have SFRs twice the isolated case (see their Table D.1). We compare with their fly bys and not their merger scenario because the galaxies in our sample are distinct systems.

### Table 4

| Sample   | $Q_{25}$ | $Q_{50}$ | $Q_{75}$ | $>2F_{50}$ | Sample Size |
|----------|----------|----------|----------|------------|-------------|
| Pair     | 1.55     | 2.61     | 4.26     | 32 ± 7%    | 72          |
| Close pair | 1.87 | 3.11     | 4.43     | 42 ± 13%   | 26          |
| Field    | 1.18     | 1.80     | 2.86     | 14 ± 1%    | 777         |

### Notes

- $^a$ Pair and field samples derive from the volume-limited sample of low $D_n4000$ galaxies, where $M_R < -20.8$. Pair galaxies are in major pairs, $|\Delta M| < 1.75$.
- $^b$ Quartile of the distribution of SSFR$_{H\alpha}$ in units of $M_\odot$ yr$^{-1}/10^{10} M_\odot$.
- $^c$ Fraction of pair galaxies with SSFR$_{H\alpha} > 2F_{50}$, where $F_{50}$ is the median of the field galaxies in the same redshift bin.
- $^d$ Close pair: $\Delta D < 25$ kpc.
Figure 14. Normalized distribution of SSFR$_{\text{H}\alpha}$ for the low $D_n4000$ pair ($N = 72$) and field galaxies ($N = 777$) in the volume-limited sample. The pair galaxies’ distributions exhibit a clear excess of high SSFR$_{\text{H}\alpha}$ compared to that of the field galaxies. The dotted line on both plots indicates the median SSFR$_{\text{H}\alpha}$ for the field galaxies. The dashed line on the pair galaxies’ plot shows the contribution from galaxies with $\Delta D < 25$ kpc.

which have not yet had a final merger. Our results are consistent with the predictions of Di Matteo et al.

One difference between our observations and the Di Matteo et al. simulations is that their maximum SFR refers to the lifetime of the galaxy; ours represents a snapshot in time. Because the most intense bursts of star formation occur over relatively short timescales in the course of the merger (see Figure 4 in Di Matteo et al.), we are unlikely to observe pair galaxies at maximum intensity. We therefore expect to measure a lower frequency than that predicted by Di Matteo et al. This prediction is consistent with our finding only one galaxy with SSFR$_{\text{H}\alpha} > 5 \times F_{50};$ Di Matteo et al. found that 15% of their major mergers have star formation enhanced by this large factor.

The frequency and strength of triggered star formation that we measure are consistent with the observations of Jogee et al. (2008), who found that the average SFRs of strongly disturbed galaxies exhibit only a modest increase over the morphologically undisturbed galaxies in their sample of $\sim 4500$ galaxies at $0.24 < z < 0.80.$ Our results are also in line with the low redshift observations of Ellison et al. (2008), who measure SFR enhancement in SDSS galaxies at $z < 0.16.$ Li et al. (2008) find that the SDSS systems with the highest SFRs are likely to have a companion, but not all systems with close companions have high SFRs.

A consistent explanation for the range of results drawn from simulations and observations is that strongly enhanced star formation is rare and short lived. Simulations can track the maximum enhancement across the lifetime of the merger; different types of pair selection probes systems in different stages of the interaction. Density effects may also reduce the impact of observations of star formation in pairs (Barton et al. 2007).

6.3. Duration of Triggered Star Formation

We use the stellar population models described in Section 2.3.1 to compare the stellar composition of pair and unpaired field galaxies. The stellar population models fit the spectra with a discrete set of starbursts of age 0.005, 0.025, 0.1, 0.3, 0.6, 0.9, 1.4, 2.5, 5, and 10 Gyr. From the models we extract the contribution of each starburst population to the flux at 5500 Å.

Figure 15 shows the ratio (pair/field) of the mean fraction of light from starburst populations as a function of starburst population age for pair and unpaired field galaxies with low $D_n4000$ in the volume-limited sample. The pair galaxies show a greater light fraction from young stellar populations up to burst ages $\sim 300–400$ Myr. The dashed line indicates a ratio of unity. Error bars are from bootstrap re-sampling; boxes indicate the inter-quartile range and the outer lines show the 95% confidence interval.

Our measurement agrees well with the results of Barton et al. (2000), who apply spectral synthesis models (Leitherer et al. 1999; Bruzual & Charlot 1996) to their data from the CfA2 Redshift Survey (Falco et al. 1999). They determine that the H$\alpha$ emission and the galaxy colors are best described by a burst with a continuous duration $\gtrsim 100$ Myr on top of the pre-existing stellar population. The simulations of Di Matteo et al. (2008) similarly suggest a merger-driven starburst duration of up to a few hundred Myr, consistent with our measured duration.

7. SUMMARY AND CONCLUSION

We examine spectroscopic properties of pair and field galaxies to quantify effects of gravitational interactions at intermediate redshift. Our sample derives from the SHELS (Geller et al. model. The pair galaxies clearly contain a larger fraction of young stellar populations up to burst ages $\sim 300–400$ Myr. The ratio of the mean fraction of flux from each starburst population dips slightly below one for burst ages $\gtrsim 500$ Myr, because the younger stellar populations contain a greater fraction of the flux in the pair galaxies.

Our measurement agrees well with the results of Barton et al. (2000), who apply spectral synthesis models (Leitherer et al. 1999; Bruzual & Charlot 1996) to their data from the CfA2 Redshift Survey (Falco et al. 1999). They determine that the H$\alpha$ emission and the galaxy colors are best described by a burst with a continuous duration $\gtrsim 100$ Myr on top of the pre-existing stellar population. The simulations of Di Matteo et al. (2008) similarly suggest a merger-driven starburst duration of up to a few hundred Myr, consistent with our measured duration.
SHELS includes 9825 galaxies and is 97.7% spectroscopically complete to $R = 20.3$ over an area of 4 deg$^2$. We select for galaxies in the redshift range $z = 0.080–0.376$. This survey represents the most complete spectroscopic sample in its redshift range. We focus on the systems that have the potential to exhibit bursts of star formation as a result of the interaction. Substantial evidence shows that major pairs are more strongly affected by the interaction. We identify a full set of major ($|\Delta M_p| < 1.75$) pairs including 622 galaxies in the redshift range $z = 0.080–0.376$, and a volume-limited subset of major pairs in the redshift range $z = 0.080–0.310$, including 327 galaxies to $M_p = -20.8$.

Within our major pair sample, we further narrow our selection using the spectroscopic index $D_n4000 = 1.44$ as the divide between systems with older stellar populations, and systems with young stellar populations that likely contain gas. We further restrict our sample to systems with low surrounding density, which we measure with a count of neighbors within a volume of comoving radius 985 kpc.

The spectroscopic diagnostics of SSFR$_H$, $D_n4000$, and a set of stellar population models enable the investigation of the strength, frequency, and timescale of triggered star formation. We show

1. The spectroscopic indicator $D_n4000$ provides a useful classification metric and corresponds closely with identification of emission line galaxies.
2. The star formation indicators SSFR$_H$, $D_n4000$, and the presence of young stellar populations exhibit an anti-correlation with $\Delta D$, demonstrating that bursts of star formation are associated with close proximity to a major companion.
3. $32 \pm 7\%$ of major pair galaxies in the volume-limited sample experience enhanced specific star formation activity at twice the median of the unpaired field galaxies. For very close pairs ($\Delta D < 25$ kpc), the fraction is 42 $\pm 13\%$. This trend is consistent with the tidal triggering picture.
4. We use stellar population models to show the burst of star formation following an interaction has a duration of $\sim$300–400 Myr. Pair galaxies show an increase over the field in the light fraction from young stellar populations for burst ages up to $\sim$300–400 Myr.

The most effective way to increase our ability to measure differences between pair and field galaxies as a function of redshift, or to determine the AGN fraction in pairs would be to observe a larger population of very close pairs ($\Delta D < 15$ kpc) at redshift $z \sim 0.3$ using small aperture spectroscopy. It is important to have high-resolution photometric data in combination with good seeing to distinguish close pairs.

This work benefited greatly from discussions with Elizabeth Barton, Nelson Caldwell, Scott Kenyon, and Lisa Kewley. We thank the members of D.F.W.’s PhD thesis committee for their comments that improved this work: Lars Hernquist, Robert Kirshner, and Andrew Szentgyorgyi. We thank the anonymous referee for a helpful and knowledgeable report. We gratefully acknowledge the contribution of the CfA’s Telescope Data Center team, especially Doug Mink, Susan Tokarz, and William Wyatt for their work with the Hectospec data reduction pipeline. We thank the Hectospec engineering team, including Robert Fata, Tom Gauron, Edward Hertz, Mark Mueller, and Mark Lacasse, and the instrument specialists Perry Berlind and Michael Calkins, along with the rest of the staff at the MMT Observatory. Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the U.S. Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS Web site is http://www.sdss.org/.

Facilities: MMT(Hectospec), Sloan, KPNO:CFT(Mosaic)

REFERENCES

Adelman-McCarthy, J., et al. 2006, ApJS, 162, 38
Allen, P. D., Driver, S. P., Graham, A. W., Cameron, E., Liske, J., & De Provis, R. 2006, MNRAS, 371, 2
Annis, J. 2001, http://home.fnal.gov/~annis/astrophys/kcorr/kcorr.html
Arp, H. 1966, Atlas of Peculiar Galaxies (Pasadena, CA: California Inst. of Technology)
Baldwin, J. A., Phillips, M. M., & Terlevich, R. 1981, PASP, 93, 5
Balogh, M. L., Morris, S. L., Yee, H. K. C., Carlberg, R. G., & Ellingson, E. 1999, ApJ, 527, 54
Barton, E. J. 1999, PhD thesis, Harvard Univ.
Barton, E. J., Arnold, J. A., Zentner, A. R., Bullock, J. S., & Wechsler, R. H. 2007, ApJ, 671, 1538
Barton, E. J., Geller, M. J., & Kenyon, S. J. 2000, ApJ, 530, 660
Barton Gillespie, E., Geller, M. J., & Kenyon, S. J. 2003, ApJ, 582, 668
Bell, E. F., et al. 2005, ApJ, 625, 23
Bergvall, N., Laurikainen, E., & Aalto, S. 2003, A&A, 405, 31
Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393
Binney, J., & Merrifield, M. 1998, Galactic Astronomy (Princeton, NJ: Princeton Univ. Press), Table 2.1, 53
Brand, K., et al. 2005, ApJ, 626, 723
Brinchmann, J., & Ellis, R. S. 2000, ApJ, 536, L77
Bruzual, A. G. 1983, ApJ, 273, 105
Bruzual, A. G., & Charlot, S. 1996, AAS CD-ROM Ser. 7, Astrophysics on Disk (Washington, DC: AAS)
Bruzual, G. A., & Charlot, S. 2003, MNRAS, 344, 1000
Calzetti, D. 2001, PASP, 113, 1449
Calzetti, D., Armus, L., Bohlin, R. C., Kinney, A. L., Koornneef, J., & Storchi-Bergmann, T. 2000, ApJ, 533, 682
Cattaneo, A., Dekel, A., Faber, S. M., & Guiderdoni, B. 2008, MNRAS, 389, 567
Cavaliere, A., & Vittorini, V. 2000, ApJ, 543, 599
Charlot, S., & Fall, S. M. 2000, ApJ, 539, 718
Cole, S., Lacey, C. G., Baugh, C. M., & Frenk, C. S. 2000, MNRAS, 319, 168
Cooper, M. C., et al. 2007, MNRAS, 376, 1445
Cowie, L. L., Songaila, A., Hu, E. M., & Cohen, J. G. 1996, AJ, 112, 839
Cox, T. J., Jonsson, P., Primack, J. R., & Somerville, R. S. 2006, MNRAS, 373, 1013
Cox, T. J., Jonsson, P., Somerville, R. S., Primack, J. R., & Dekel, A. 2008, MNRAS, 384, 386
Dasyra, K. M., Tacconi, L. J., Davies, R. I., Genzel, D. L., Naab, T., Burkert, A., Veilleux, S., & Sanders, D. B. 2006, ApJ, 638, 745
De Propris, R., Conselice, C. J., Liske, J., Driver, S. P., Patton, D. R., Graham, A. W., & Allen, P. D. 2007, ApJ, 666, 212
de Ravel, L., et al. 2009, A&A, 498, 379
Di Matteo, P., Bournaud, F., Martig, M., Combes, F., Melchior, A.-L., & Semelin, B. 2008, A&A, 492, 31
Di Matteo, P., Combes, F., Melchior, A.-L., & Semelin, B. 2007, A&A, 468, 61
Donzelli, C. J., & Pastoriza, M. G. 1997, ApJS, 111, 181
Driver, S. P., Liske, J., Cross, N. J. G., De Propris, R., & Allen, P. D. 2005, MNRAS, 360, 81
Ellison, S. L., Patton, D. R., Simard, L., & McConnell, A. W. 2008, AJ, 135, 1877
Estrada, J., Sehusatti, E., & Friedman, J. A. 2009, ApJ, 692, 265
Fabricant, D. G., Kurtz, M. J., Geller, M. J., Caldwell, N., & Woods, D. 2008, PASP, 120, 1222
Fabricant, D. G., et al. 2005, PASP, 117, 1411
Falco, E., et al. 1999, PASP, 111, 438
Geller, M. J., Dell’Antonio, I. P., Kurtz, M. J., Ramella, M., Fabricant, D. G., Caldwell, N., Tyson, J. A., & Wittman, D. 2005, ApJ, 635, L125
Geller, M. J., Kenyon, S. J., Barton, E. J., Jarret, T. H., & Kewley, L. J. 2006, AJ, 132, 2243
Geller, M. J., Kurtz, M. J., Dell’Antonio, I., Ramella, M., & Fabricant, D. 2010, ApJ, 709, 832
Gerke, B. F., et al. 2007, MNRAS, 376, 1425
Guzman, R., Gallegos, J., Koo, D. C., Phillips, A. C., Lowenthal, J. D., Faber, S. M., Illingworth, G. D., & Vogt, N. P. 1997, ApJ, 489, 559
Hopkins, P. F., Hernquist, L., Cox, T. J., & Kereš, D. 2008, ApJS, 175, 356
Hubble, E., & Humason, M. L. 1931, ApJ, 74, 43
Hummel, E. 1981, A&A, 96, 111
Jogee, S., et al. 2008, in ASP Conf. Ser. 396, Formation and Evolution of Galaxy Disks, ed. J. G. Funes & E. M. Corsini (San Francisco, CA: ASP), 337
Jones, B., & Stein, W. A. 1989, AJ, 98, 1557
Juneau, S., et al. 2005, ApJ, 619, L135
Kauffmann, G., White, S. G., Heckman, T. M., Ménard, B., Brinchmann, J., Charlton, S., Tremonti, C., & Brinkmann, J. 2004, MNRAS, 353, 713
Kauffmann, G., et al. 2003, MNRAS, 341, 54
Keel, W. C. 1993, AJ, 106, 1771
Kennicutt, R. C., Jr. 1998, ARA&A, 36, 189
Kennicutt, R. C., Jr., & Keel, W. C. 1984, ApJ, 279, L5
Kennicutt, R. C., Jr., Roettiger, K. A., Keel, W. C., van der Hulst, J. M., & Hummel, E. 1987, AJ, 93, 1011
Kewley, L. J., Groves, B., Kauffmann, G., & Heckman, T. 2006, MNRAS, 372, 961
Kewley, L. J., Jansen, Rolf, A., Geller, & Margaret, J. 2005, PASP, 117, 227
Kodama, T., et al. 2004, MNRAS, 350, 1005
Kurtz, M. J., & Mink, D. J. 1998, PASP, 110, 934
Lambas, D. G., Tissera, P. B., Alonso, M. S., & Coldwell, G. 2003, MNRAS, 346, 1189
Larson, R. B., & Tinsley, B. M. 1978, ApJ, 219, 46
Le Borgne, D., & Rocca-Volmerage, B. 2002, A&A, 386, 446
Le Févre, O., et al. 2005, A&A, 439, 845
Leitherer, C., et al. 1999, ApJS, 123, 3
Li, C., Kauffmann, G., Heckman, T. M., Jing, Y. P., & White, S. D. M. 2008, MNRAS, 385, 1903
Lin, L., et al. 2007, ApJ, 660, L51
Liske, J., Lemon, D. J., Driver, S. P., Cross, N. J. G., & Couch, W. J. 2003, MNRAS, 344, 307
Liu, C. T., & Kennicutt, R. C., Jr. 1995, ApJ, 450, 547
Markwardt, C. B. 2009, in ASP Conf. Ser. 411, Astronomical Data Analysis Software and Systems XVIII ed. D. A. Bohlender, D. Durand, & P. Dowler (San Francisco, CA: ASP)
Mignoli, M., et al. 2005, A&A, 437, 883
Mihos, J. C., & Hernquist, L. 1996, ApJ, 464, 641
Mink, D. J., Wyatt, W. F., Caldwell, N., Conroy, M. A., Furesz, G., & Tokarz, S. P. 2007, in ASP Conf. Ser. 376, Astronomical Data Analysis Software and Systems XVI, ed. R. A. Shaw, F. Hill, & D. J. Bell (San Francisco, CA: ASP), 249
Muller, G. P., et al. 1998, Proc. SPIE, 3355, 577
Nikolic, B., Cullen, H., & Alexander, P. 2004, MNRAS, 355, 874
Noeske, K. G., et al. 2007, ApJ, 660, L47
Patton, D. R., Grant, J. K., Simard, L., Pritchet, C. J., Carlberg, R. G., & Borne, K. D. 2005, AJ, 130, 2043
Patton, D. R., et al. 2002, ApJ, 565, 208
Rines, K., Geller, M. J., Kurtz, M. J., & Diaferio, A 2003, AJ, 126, 2152
Sekiguchi, K., & Walstencreft, R. D. 1992, MNRAS, 255, 581
Shioya, Y., et al. 2008, ApJS, 175, 128S
Smith, B. J., Struck, C., Appleton, P. N., Charmandaris, V., Reach, W., & Eiter, J. J. 2005, AJ, 130, 2117
Spergel, D., et al. 2003, ApJS, 148, 175S
Strateva, I., et al. 2001, AJ, 122, 1861
Tissera, P. B., Domínguez-Tenreiro, R., Scannapieco, C., & Sáiz, A. 2002, MNRAS, 333, 327
Tran, K.-V. H., et al. 2005, ApJ, 627, L25
Tremonti, C. A., et al. 2004, ApJ, 613, 898
van Dokkum, P. G. 2005, AJ, 130, 2647
Vergani, D., et al. 2008, A&A, 487, 89
Wechsler, R. H., Bullock, J. S., Primack, J. R., Kravtsov, A. V., & Dekel, A. 2002, ApJ, 568, 52
Westra, E., Geller, M. J., Kurtz, M. J., Fabricant, D. G., & Dell’Antonio, I. 2010, ApJ, 708, 534
Wittman, D., Dell’Antonio, I. P., Hughes, J. P., Margoniner, V. E., Tyson, J. A., Cohen, J. G., & Norman, D. 2006, ApJ, 643, 128
Wittman, D. M., et al. 2002, Proc. SPIE, 4836, 73
Woods, D. F., & Geller, M. J. 2007, AJ, 134, 527
Woods, D. F., Geller, M. J., & Barton, E. B. 2006, AJ, 132, 197
Yee, H. K. C., et al. 2001, ApJS, 129, 475