GALAXY PAIRS IN THE SLOAN DIGITAL SKY SURVEY. I. STAR FORMATION, ACTIVE GALACTIC NUCLEUS FRACTION, AND THE LUMINOSITY/MASS–METALLICITY RELATION

SARA L. ELLISON1, DAVID R. PATTON1,2, LUC SIMARD3, AND ALAN W. McCONNACHIE1
1 Department of Physics & Astronomy, University of Victoria, 3800 Finnerty Rd, Victoria, V8P 1A1, British Columbia, Canada; sarae@uvic.ca, alan@uvic.ca
2 Department of Physics & Astronomy, Trent University, 1600 West Bank Drive, Peterborough, Ontario, K9J 7B8, Canada; dpatton@trentu.ca
3 National Research Council of Canada, Herzberg Institute of Astrophysics, 5071 West Saanich Road, Victoria, British Columbia, V9E 2E7, Canada; luc.simard@nrc-cnrc.gc.ca
Received 2007 June 5; accepted 2008 March 2; published 2008 April 11

ABSTRACT

We present a sample of 1716 galaxies with companions within Δv < 500 km s⁻¹, rp < 80 h⁻¹ kpc and stellar mass ratio 0.1 < M₁/M₂ < 10 from the Sloan Digital Sky Survey Data Release 4. The galaxy pairs are selected from the Main Galaxy Sample using stringent and well-understood criteria for redshift, spectral quality, available stellar masses, and metallicities. In agreement with previous studies, we find an enhancement in the star-formation rate (SFR) of galaxy pairs at projected separations <30–40 h⁻¹ kpc. In addition, we find that this enhancement is highest (and extends to the greatest separations) for galaxies of approximately equal mass, the so-called major pairs. However, SFR enhancement can still be detected for a sample of galaxy pairs whose masses are within a factor of 10 of each other. Based on these results, we define a sample of close pairs (Δv < 500 km s⁻¹, rp < 30 h⁻¹ kpc, and 0.1 < M₁/M₂ < 10) which we use to investigate interaction-induced effects in the luminosity–metallicity (LZ) relation. In addition, we find that this enhancement to lower metallicities (by ~0.1 dex) for a given luminosity for galaxies in pairs compared to the control sample. We also present the first mass–metallicity (MZ) relation comparison between paired galaxies and the field and again find an offset to lower metallicities (by ~0.05 dex) for a given mass. The smaller offset in the MZ relation indicates that both higher luminosities and lower metallicities may contribute to the shift of pairs relative to the control in the LZ relation. We show that the offset in the LZ relation depends on galaxy half-light radius, rₕ. Galaxies with rₕ < 3 h⁻¹ kpc and with a close companion show a 0.05–0.1 dex downward offset in metallicity compared to control galaxies of the same size. Larger galaxies do not show this offset and have LZ and MZ relations consistent with the control sample. We investigate the physical impetus behind this empirical dependence on rₕ and consider the galaxy’s dynamical time and bulge fractions as possible causes. We conclude that the former is unlikely to be a fundamental driver of the offset in the LZ relation for paired galaxies, but that bulge fraction may play a role. Finally, we study the active galactic nucleus (AGN) fraction in both the pair and control sample and find that whilst selecting galaxies in different cuts of color and asymmetry yields different AGN fractions, the fraction for pairs and the control sample are consistent for a given set of selection criteria. This indicates that if AGNs are ignited as a result of interactions, this activity begins later than the close pairs stage (i.e. once the merger is complete).

Key words: galaxies: abundances – galaxies: ISM

1. INTRODUCTION

The evolutionary path followed by a galaxy is shaped by its merger history, which in turn depends on its environment. This dependence is epitomized by the properties of galaxies in rich environments such as clusters (e.g., Dressler 1980; Whitmore et al. 1993; Balogh et al. 1998, 1999; Poggianti et al. 1999; Pimbblet et al. 2002; Wake et al. 2005). The effect of such high-density living is generally to suppress star formation, through mechanisms that can include cluster tidal fields, gas (ram pressure) stripping, and strangulation (e.g., Byrd & Valtonen 1990; Moore et al. 1999; Diaferio et al. 2001). From this point of view, one may expect to see the most extreme effects of density-induced properties from environments that are rich on scales of a few hundred kpc. However, it is now emerging that density on smaller scales can be the major impetus behind galaxy evolution (e.g., Lewis et al. 2002; Gomez et al. 2003; Blanton & Berlind 2007). Galaxies in compact groups, for example, exhibit a clear tendency toward lower metallicities and older stellar populations compared with isolated galaxies (e.g., Proctor et al. 2004; Mendes de Oliveira et al. 2005; de la Rosa et al. 2007). On these smaller scales, galaxy mergers provide the most obvious mechanism for change. Simulations predict that prior to halted star formation, there should be a phase of increased activity (e.g., Di Matteo et al. 2005) which precedes the final merger, particularly in gas-rich systems. Observations of early-stage galaxy interactions will therefore complement those of rich environments to provide a more complete picture of the evolutionary process. In this sense, close pairs or morphologically disturbed galaxies may be the pre-cursors to the “red-and-dead” galaxies seen in dense environments.

The seminal study of the effect of interactions on galaxy colors is the work of Larson & Tinsley (1978). They found that disturbed galaxies in the Arp catalog had a wider spread of colors, including more blue galaxies, than the field galaxies in the Hubble atlas. In the last 30 years, this distinction in color has been confirmed numerous times in larger samples. In general, galaxies with close companions, including those showing clear signs of morphological asymmetry, tend to have bluer (integrated) optical colors (e.g., Carlberg et al. 1994; Patton et al. 1997, 2005). These results are indicative of enhanced star formation, a scenario supported by high equivalent widths of Hα emission when spectra are available.
As the merging process advances, an expected consequence of the gas funneling might be the ignition of an active galactic nucleus (AGN). Effectively all galaxies are thought to harbor a nucleus (AGN). Effectively all galaxies are thought to harbor a given luminosity, compared to a control sample. Since their spectra included only the central 10% of the galaxies’ light, Kewley et al. (2006a), who found a shift toward lower metallicities by ~0.2 dex in galaxy pairs for a given luminosity, compared to a control sample. Since their spectra included only the central 10% of the galaxies’ light, Kewley et al. (2006a) interpreted this result as the signature of metal-poor gas that had been funneled into the center of the galaxies.

As the merging process advances, an expected consequence of the gas funneling might be the ignition of an active galactic nucleus (AGN). Effectively all galaxies are thought to harbor black holes at their centers, the masses of which correlate on scales of a few tens of kpc. The induced star-formation activity associated with interactions and mergers is expected to have an impact on the metallicity of galaxy pairs. There is a well-established correlation between luminosity and metallicity, which is a manifestation of a more fundamental stellar mass–metallicity relation (e.g., Tremonti et al. 2004; Salzer et al. 2005; Lee et al. 2006), which is likely be be “disturbed” for interacting galaxies. It is not clear a priori how these scaling relations between luminosity, mass, and metallicity might be affected by interactions. The galaxy luminosity may significantly increase due to the additional star formation experienced as a result of the merger. The overall metallicity of an interacting galaxy may first appear to decrease as metal-poor gas flows into its inner regions. However, we eventually expect the metallicity to increase as the star formation proceeds and eventually returns its nucleosynthetic products into the interstellar medium. The end point metallicity will depend on a number of factors such as the mass and metallicity of the inflowing gas, efficiency of the starburst, and the metal yield. The first major observational study of these effects was presented by Kewley et al. (2006a), who found a shift toward lower metallicities by ~0.2 dex in galaxy pairs for a given luminosity, compared to a control sample. Since their spectra included only the central 10% of the galaxies’ light, Kewley et al. (2006a) interpreted this result as the signature of metal-poor gas that had been funneled into the center of the galaxies.

As the merging process advances, an expected consequence of the gas funneling might be the ignition of an active galactic nucleus (AGN). Effectively all galaxies are thought to harbor black holes at their centers, the masses of which correlate on scales of the galaxy’s bulge component as measured through stellar velocity dispersion (e.g., see Marconi et al. 2004; Shankar et al. 2004; Ferrarese & Ford 2005 for a review). Infall of gas onto the black hole via a galaxy interaction is a natural way to engage nuclear activity. Indeed, it has previously been noted that low-redshift Seyfert galaxies often occur in groups (e.g., Stauffer 1982) and that a high fraction of galaxies close to AGNs appear to be interacting (see the review by Barnes & Hernquist 1992). However, although Seyfert galaxies may show evidence for recent nuclear star formation (e.g., Storchi-Bergmann et al. 2001), there is so far no evidence that AGN activity is enhanced in denser environments relative to the field, including in close pairs (e.g., Schmitt 2001; Sorrentino et al. 2006; Alonso et al. 2007). Instead, AGN activity is best signaled by morphological disturbances (e.g., Barnes & Hernquist 1992; Alonso et al. 2007).

Investigating the myriad effects of galaxy interactions clearly requires measurements of a suite of properties, including stellar mass, star-formation rates (SFRs), AGN contribution, metallicities, color, and morphology as characterized by measures such as bulge-to-total ratios and asymmetry. Whilst many of these properties have been previously studied (see above references) no work to date has been able to combine all of these parameters for a single, large sample. In this regard the Sloan Digital Sky Survey (SDSS) is an excellent resource with both photometric and quality spectroscopic data available for over half a million galaxies in the Data Release 4 (DR4). In this paper series (see also D. R. Patton et al. 2008, in preparation, henceforth Paper II, and other forthcoming papers) we have combined SDSS photometry with the results of spectral synthesis modeling, which yield estimates for properties such as the stellar mass, metallicity, SFR and bulge, and disk image decomposition in five filters (L. Simard 2008, in preparation) to yield morphological parameters. Therefore, this sample provides the first coherent dataset for which such a wide suite of galaxy parameters can be investigated, and the relationships between these properties studied in a systematic way. Moreover, the statistical power of the SDSS allows us to be highly selective in the way we form our sample. Therefore, although our final pairs sample is not the largest to date (see Alonso et al. 2006; Paper II), our selection criteria are amongst the most stringent. This is particularly important when using spectroscopic data to determine quantities such as metallicity, where the combination of several emission lines can become very sensitive to poor signal-to-noise ratio (S/N; Kewley & Ellison, 2008). In Paper II, we investigate the photometric properties of SDSS galaxies in close pairs. In this paper, we combine the basic survey properties of a sample of galaxy pairs with spectroscopic properties determined by, e.g., Kauffmann et al. (2003b), Brinchmann et al. (2004), Tremonti et al. (2004) and Kewley & Ellison (2008). This allows us to investigate the sensitivity of metallicity, AGN incidence, mass, and SFR on a galaxy’s proximity to a companion.

The layout of this paper is as follows. In Section 2, we describe the compilation of our galaxy pairs and control samples. In Section 3, we use the wide pairs sample defined in Section 2 to study the effect of pair proximity and relative stellar masses on SFR. Based on these results, we define a sample of close pairs which are most likely to exhibit interaction-induced effects. In Section 4, we investigate the luminosity–metallicity (LZ) and mass–metallicity (MZ) relations and in Section 5 the AGN fraction in galaxies with close companions. Each of the three science sections (Sections 3–5) can be read largely independently, although we recommend that all readers understand...
the sample selection laid out in Section 2. We summarize the full results of this paper in Section 6.

We adopt a concordance cosmology of $\Omega_\Lambda = 0.7$, $\Omega_M = 0.3$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

2. SAMPLE SELECTION

Our galaxy pairs sample is selected from the DR4 of the SDSS and includes requirements based on both photometric and spectroscopic selection. The imaging portion of the DR4 covers 6670 deg$^2$ in five bands and the spectroscopic catalog is magnitude limited for extinction-corrected Petrosian $r < 17.77$. To construct our galaxy samples, we use the DR4 catalog of 567,486 galaxies compiled by the Munich group.$^4$ Pipeline processing which fits galaxy templates and spectral synthesis models to the spectra yields physical properties such as stellar masses and SFRs as well as measurements of line fluxes (e.g., Kauffmann et al. 2003b; Brinchmann et al. 2004; Tremonti et al. 2004). Although metallicities are available for the majority of these galaxies, Ellison & Kewley (2005) and Kewley & Ellison (2008) have shown that different empirical calibrations can yield metallicities that vary by up to a factor of 3. The Tremonti et al. (2004) metallicities are amongst the highest of these calibrations. We used the published line fluxes to calculate the metallicities according to the “recommended” method of Kewley & Dopita (2002) which solves iteratively for metallicity and ionization parameter. We made this selection for two reasons. First, the calibration of Kewley & Dopita (2002) yields one of the tightest mass–metallicity relations (Kewley & Ellison 2008). Second, the metallicity conversions between various strong line diagnostics presented by Kewley & Ellison (2008) show that conversions to/from the Kewley & Dopita (2002) calibration exhibit one of the smallest scatters. Other properties used in this paper (e.g., SFR and stellar mass) are taken directly from the catalogs made generously available by the Munich team.

Our sample selection differs importantly from that of Paper II, which focuses on the photometric properties of galaxies in pairs. Although spectroscopic redshifts and stellar masses were required for pair selection in Paper II, no other spectral requirement was included in the selection criteria. However, since we will be focused on properties that are derived from spectra, such as SFR and metallicity, our selection criteria are more stringent, and our sample correspondingly smaller. Moreover, since our metallicity determinations require moderately high S/N in the emission lines (see below), the galaxies in this sample are necessarily star forming or AGN dominated. There are no quiescent, inactive (“red-and-dead”) galaxies in our sample.

From the catalog of over half a million SDSS DR4 galaxies we select galaxies that fulfill the following criteria.

1. Galaxies must have extinction-corrected Petrosian magnitudes in the range $14.5 < r < 17.77$. The faint limit matches the criterion of Sloan’s Main Galaxy Sample and ensures a high completeness and unbiased selection for mass estimates (see below). The bright limit avoids deblending problems that confuse the identification of close pairs (Strauss et al. 2002). We also required that the objects were classified as galaxies from the SDSS imaging (SpecPhoto.Type = 3) and were classified spectrally as either a galaxy or QSO (SpecPhoto.SpectClass = 2,3).

2. Galaxies must be unique spectroscopic objects. We reject duplicates in the initial sample of 567,486 galaxies by including the single galaxy that has been classified as “science worthy” (flag scienceprimary = 1 in the SDSS “SpecObjAll” table). In a handful ($< 20$) of cases, a single photometric object (galaxy) is associated with two spectroscopic objects. Such cases are often highly disturbed galaxies which, for example, have double nuclei or distinctive tidal tails. We reject these objects from our sample, but will revisit them in a future paper.

3. The redshift must be $z < 0.16$ and the SDSS SpecObjAll parameter which measures the redshift confidence $z_{conf} > 0.7$. We exclude higher redshifts since there is a tail of rare galaxies at $z > 0.16$ which is not seen in the pairs sample, simply due to small number statistics. Imposing a redshift cut is common practice in pairs’ studies in order to limit the effects of both evolution and aperture effects (e.g., Kewley et al. 2006a; Woods & Geller 2007), although we re-visit the redshift distribution at a more sophisticated level below.

4. The error on the emission line flux must be less than one-fifth of the measured flux in all of the following emission lines: [O II] $\lambda 3727$, H$\beta$, [O III] $\lambda 5007$, H$\alpha$, [N II] $\lambda 6584$ and [S II] $\lambda 6717, 6731$. This criterion ensures a high effective S/N which in turn facilitates accurate classification of the galaxies as either star forming or AGN dominated (e.g., Kewley et al. 2001; Kauffmann et al. 2003a) and for accurate metallicity determination from empirical strong line diagnostics (e.g., Kobulnicky et al. 1999; Kewley & Ellison 2008). This criterion automatically selects star-forming galaxies and will exclude passively evolving or “red-and-dead” galaxies, as well as galaxies with very high extinction and metal-poor galaxies with faint emission lines.

5. Stellar mass estimates must be available (e.g., Kauffmann et al. 2003b; Tremonti et al. 2004). These are available in the Munich catalogs and are derived from spectral template fitting and have typical uncertainties $\sim 0.1$ dex. Drory et al. (2004) have shown that the spectrally-determined stellar masses compare well with those derived from optical and IR colors and they are good surrogates for the dynamical mass when $\log M_* > 10 M_\odot$ (see also Brinchmann & Ellis 2000). At lower stellar masses, $M_*$ is larger than the dynamical mass by $< 0.4$ dex (Drory et al. 2004).

6. Metallicities as calculated by the Kewley & Dopita (2002) diagnostic must be available, although we do not require that both galaxies in a pair have known metallicities.

7. Galaxies must be classified as star forming and not AGN dominated, according to the line diagnostic criteria given in Kewley et al. (2001). We impose this criterion since metallicities derived from strong line calibrations assume a stellar ionizing background and are not applicable if there is a (local) AGN component. Recently, Kewley et al. (2006b) have proposed a new AGN removal scheme that is more stringent than the original Kewley et al. (2001) criteria. However, Kewley & Ellison (2008) have shown that, for metallicities derived from the Kewley & Dopita (2002) strong line calibration, the mass–metallicity relation is identical for the Kewley et al. (2001, 2006b) AGN filtering schemes. We remove the criterion of AGN exclusion for our study of AGN fractions in Section 5.

From this master sample, we then select galaxies with companions that we shall refer to as “galaxy pairs,” although $\sim 5\%$ consist of galaxies in triples and a minority of higher
For inclusion in the sample of galaxy pairs, we further require that:

8. Galaxies have one or more companions with projected physical separations of $r_p < 80 \, h^{-1}_{70} \text{kpc}$. Although previous observational and theoretical studies have found $30 \, h^{-1}_{70} \text{kpc}$ ($\sim 20 \, h^{-1}_{100} \text{kpc}$) to be the approximate scale on which pairs start to exhibit distinct properties compared with the field (e.g., Barton et al. 2000; Patton et al. 2000; Lambas et al. 2003; Alonso et al. 2004; Nikolic et al. 2004; Perez et al. 2006a), we consider wider pairs in order to investigate trends in separation. All pairs with separations $r_p < 15 \, h^{-1}_{70} \text{kpc}$ were inspected visually, since erroneous pair identifications do occur at small separations. The majority of spurious pairs were at $r_p < 5 \, h^{-1}_{70} \text{kpc}$ and occur, e.g., when an H\textsc{ii} region in a single galaxy is identified as separate galaxy. For separations $r_p > 10 \, h^{-1}_{70} \text{kpc}$, the fraction of spurious pair identifications is less than 1%.

9. The rest-frame velocity difference of a galaxy pair must be $\Delta v < 500 \, \text{km s}^{-1}$. This velocity offset was selected in order to provide a balance between contamination and statistics. Although a much smaller velocity separation reduces contamination, it also reduces the overall sample size, which may ultimately become a limiting factor in pair statistics. The trade-off between these effects has been addressed in Patton et al. (2000).

10. Relative stellar masses must be within a factor of 10. Although we expect to see more interaction-induced effects in pairs of almost equal mass (e.g., Woods et al. 2006; Cox et al. 2008; Woods & Geller 2007), we include a wide range of mass ratios in order to investigate the relative impact of major and minor interactions.

If a galaxy fulfills the first seven of the above criteria, but not the latter three, it is a candidate for our control sample. A galaxy fulfilling all ten criteria may be potentially included in our sample of wide pairs. Before constructing the final control and wide pairs samples, we make two further restrictions in order to make the two samples directly comparable. Both of these restrictions are driven by the requirement that the redshift and stellar mass distributions of the pairs and control samples should be statistically indistinguishable. This is an important requirement since the distributions of stellar mass and redshift can impact the observed ranges in properties such as luminosity and SFR. The redshifts of the galaxies selected simply from the above criteria are shown in Figure 1 where the histogram of pairs' redshifts has been roughly normalized to the number of galaxies in the control sample for display purposes. Clearly,
the redshift distribution of the pairs is skewed toward lower values than the control, which could potentially bias our results. This can largely be understood by examining the lower panel of Figure 1 which shows the projected separation of pairs as a function of redshift and demonstrates a clear excess of pairs at low redshift and wide separation. This is mostly due to the spectroscopic follow-up strategy of the SDSS survey. There is a 55′′ fiber collision limit due to the size of the fiber housing, which prevents pairs with angular separations less than this from being observed spectroscopically on the same plate.3 However, contiguous plates have considerable overlap and some sky regions are observed more than once, so that many close pairs exist in the final spectroscopic catalog. The net effect on our preliminary pairs sample is that the spectroscopic completeness drops sharply below 55′′, leading to the relative overabundance of pairs with wide physical separations at low redshifts in Figure 1. Fortunately, it is straightforward to model and correct for this effect. Patton & Atfield (2008) find that the ratio of spectroscopic to photometric pairs decreases from ~80% at angular separations θ > 55′′ to ~26% (on average) at smaller separations. We therefore make a first attempt to correct the disparity in redshift distributions by randomly excluding 54/80 = 67.5% of galaxies in pairs with θ > 55′′. We use this cull to compile our final wide pairs sample, which contains 1915 paired galaxies before AGN removal and 1716 galaxies with one or more companions after AGN removal.

When the stellar mass ratio of the pairs is not highly discrepant (0.3 < M1/M2 ≤ 3) the cull described above yields redshift distributions for the pairs and control samples that are statistically indistinguishable. However, for more contrasting mass ratios, the redshift distributions remain statistically different. This is a common, well-known feature of pairs samples (e.g., Patton et al. 2000, 2005) and is due to the magnitude-limited nature of the parent galaxy sample and the associated limit in dynamic range. Pairs with very disparate stellar mass ratios are biased toward low redshifts, because the magnitude limit of the survey hinders their detection (i.e., detection of a much lower mass, fainter companion) at higher redshifts. Since we want to be able to study pairs with stellar mass ratios up to 10, the control sample requires further culling. At this point, a simple prune in redshift is insufficient, due to the strong correlation between mass and redshift. At z ≤ 0.05 galaxies with stellar masses ranging from approximately 10^{8.5}–10^{11} M_☉ are detected. At higher redshifts, the lower-mass galaxies are no longer detected, since they are generally too faint. We therefore have to prune the control sample simultaneously in stellar mass and redshift. This is achieved by matching one control galaxy to each paired galaxy in mass-redshift space and repeating (without replacement) as many times as possible while requiring that the Kolmogorov–Smirnov (KS) probability of the control–pair mass and redshift distributions be consistent with each other at at least the 30% level. The matching process is done before any removal of AGN-dominated galaxies so that the analysis of Section 5 (on AGN fractions) can be achieved. For each of the 1915 (pre-AGN removal) paired galaxies, there are 23 control galaxies, i.e. the control sample contains 44,045 galaxies before AGN-dominated galaxies are removed. The KS probabilities that these samples of pairs and control galaxies are indistinguishable in redshift and stellar mass are 32% and 34%, respectively (i.e., no formal statistical difference). Once the AGN-dominated galaxies have been removed, as is required for the majority of our analysis, the samples are reduced to 1716 paired galaxies and 40,095 control galaxies, a reduction in each case by approximately 10%. Figure 2 shows the redshift and stellar mass distributions for these fiducial samples. For both paired and control samples, the mean stellar mass is log M_☉ = 10.1 M_☉ and the mean redshift is z = 0.073. We can now be confident that our control sample is well matched to our pairs sample and should contain no observational bias that will affect our assessment of proximity-induced effects.

The strict selection criteria that we impose mean that our sample of galaxies is not complete in either magnitude or volume. As noted above, the S/N criterion in particular will lead to a sample that excludes (at least some) galaxies that are highly reddened, very metal-poor and not actively star forming. However, the same selection biases will apply equally to the control and the pairs samples, allowing us to make differential comparisons between the two. As described in the above discussion, our sample of pairs is also not complete. This should not introduce any bias into our pairs sample, since spectroscopic incompleteness does not depend significantly on the intrinsic properties of the galaxies. However, due to spectroscopic incompleteness, many true pairs will have a redshift measured for only one member galaxy, which may then fall into the control sample. Fortunately, any resulting contamination of the control sample is negligible, since only ~2% of galaxies are found in close pairs (see Patton & Atfield 2008).

Given that we are interested in the effects of mergers/interactions, it is also important to acknowledge the fact that some of the pairs in our sample will not be close enough for such encounters to occur. This contamination is on the order of 50% for the closer pairs (r_p < 30 h^{-1} Mpc) in our sample (Patton & Atfield 2008) and rises as pair separation increases (Alonso et al. 2004; Perez et al. 2006a). While we do not attempt to correct for this explicitly, we infer that (a) any differences seen between close pairs and the control sample are likely to be underestimated and (b) the wider pairs are likely to suffer from increasing contamination due to non-interacting systems.

One other parameter that may affect measured spectral properties is the fiber covering fraction (CF). Although aperture effects are likely to affect galaxy metallicities (Kewley et al. 2005; Ellison & Kewley 2005) we do not make any a priori cuts in CF. This is mainly because, after the above culls, the CFs are consistent between the pairs and control samples, see Figure 2. Moreover, we will be explicitly investigating the impact of CF, which is calculated by comparing the galaxy’s photometric g'-band Petrosian magnitude with the fiber magnitude in the same filter, as a free parameter in Sections 3 and 4. However, we note that the quantities of stellar mass and SFR are corrected for aperture effects (Brinchmann et al. 2004) and therefore represent total quantities.

It is worth noting that one of the novel properties of our sample is the stellar mass selection criterion, whereas most previous samples have made no requirement on the relative fluxes/masses of their visually identified pairs. Moreover, when cuts have been made in order to investigate the effect of relative mass, flux is usually used as a surrogate for mass (e.g., Woods et al. 2006; Woods & Geller 2007). In Figure 3, we show the impact of this assumption by plotting relative fluxes versus relative stellar masses. The fact that the distribution of flux to mass ratios is flatter than 1:1 means that for a given flux ratio cut the completeness rate for the same mass ratio is quite high, but the contamination is significant. For example, a flux

---

3 At z = 0.05, 1″ ~ 1 h^{-1} 70 kpc.

5
Figure 2. Histograms of redshift (top panel), mass (middle panel), and $g$-band CF (bottom panel) of our final control galaxy (solid) and wide pairs (dashed) samples, with the latter scaled for display purposes.

Figure 3. Comparison between the relative $r$-band fluxes and relative masses in the wide pairs sample. The solid diagonal line shows a one-to-one relationship between flux and mass ratios.

selection which requires a ratio within 2:1 selects 86% of galaxy pairs with masses whose ratios are within 2:1. However, 46% of the galaxies selected by this flux cut will have actual mass ratios outside the 2:1 range, leading to a high contamination rate. Selection by relative flux could therefore potentially dilute properties that depend sensitively on relative stellar mass. The reason that the correlation between relative fluxes and masses is flatter than unity in Figure 3 can be understood in terms of specific SFRs (SSFRs). Recently, Zheng et al. (2007) have shown convincingly that SSFR, i.e. SFR per unit mass, is higher for lower-mass galaxies. In turn, this broadly translates to a higher flux per stellar mass ($F/M$) for lower-mass galaxies. Therefore, when the $M_1/M_2$ ratio is less than unity, i.e. the low-mass galaxy is in the numerator, this translates to a generally higher $F_1/F_2$, because $F_1/M_1 > F_2/M_2$.

With the stringent criteria outlined above, we have not only constructed one of the largest, but also one of the most rigorously selected samples of galaxy pairs to date. Moreover, with the combination of a wide range of derived spectral properties, photometric measurements, and morphological decomposition, we have an extensive arsenal with which to tackle the effects of galaxy proximity.

3. STAR-FORMATION RATE IN GALAXY PAIRS

In this section, we investigate the effects of projected separation, relative stellar masses, and fiber CF on the SFR of paired
Figure 4. SFR for galaxies with a companion as a function of pair separation for three different mass ratio samples. The SFRs have all been normalized to the median control value for that mass range. This figure shows an increase in SFR relative to the field for projected separations $r_p < 30 h_70^{-1}$ kpc for all mass ratios. As the disparity in masses decreases (from top panel to bottom), this enhancement increases in magnitude, significance, and out to larger separations. The apparent increase in SFR at $r_p > 50 h_70^{-1}$ kpc is due to contamination effects; see the text for details.

In the top panel of Figure 4 we show the SFR as a function of galaxy separation for the wide pairs in our sample. The figure demonstrates that galaxies in pairs with separations $\leq 30 h_70^{-1}$ kpc have a median SFR that is higher than the control galaxies, by up to 40%, at 1–2σ significance. This result is consistent with previous studies of SFRs in close pairs of galaxies (e.g., Barton et al. 2000; Lambas et al. 2003; Nikolic et al. 2004; Geller et al. 2006). However, Barton et al. (2007) have suggested that the level of excess star formation in close pairs may have been underestimated in these previous works due to the typically higher density environments inhabited by pairs relative to control galaxies. This conclusion may also apply to this work, although we discuss this further in the next subsection.

3.1. Star Formation and Relative Galactic Stellar Mass

We expect (e.g., Lambas et al. 2003; Woods et al. 2006; Bekki et al. 2006; Cox et al. 2008; Woods & Geller 2007) that pairs with almost equal masses (“major mergers/interactions”) will exhibit more pronounced interaction-induced effects than unequal (“minor”) mass encounters. Although dynamical mass may be the fundamental parameter which governs the outcome of galaxy interactions, stellar mass is both more readily determined from observations and is a reasonable surrogate for dynamical mass above $10^{10} M_\odot$ (e.g., Brinchmann & Ellis 2000; Drory et al. 2004). Moreover, stellar mass is a quantity that is directly traced through many simulations, e.g., the minor pairs models of Cox et al. (2008).

Only a handful of simulations have studied the effect of star formation in minor mergers either in general (Mihos & Hernquist 1994; Cox et al. 2008) or for specific cases (e.g., Mastroietti et al. 2005 for the Milky Way–LMC). Based on this limited modeling, it has been found that induced central star formation in the larger galaxy of an unequal mass merger can eventually occur, albeit at a lower level than expected in a major merger, and usually when the interaction is well advanced, i.e., after several gigayears. In this section, we investigate whether unequal mass pairs can be affected by galaxy proximity and compare our results with pairs whose galaxies have comparable stellar masses. The only previous observational studies to assess the effects in minor mergers in close galaxy pairs were those
of Woods et al. (2006) and Woods & Geller (2007). The latter paper, which benefits from significantly better statistics than the former, finds that the specific SFR of the less massive (as inferred from a fainter magnitude) galaxy in a minor pair is enhanced compared to the field, whereas the more massive galaxy is not. However, these two previous studies relied upon relative magnitudes, and as we pointed out in Section 2, this can lead to a high rate of contamination. In this work, we use the measured stellar masses, corrected for aperture bias, determined by spectral modeling and compare our results to the flux-selected minor pairs of Woods & Geller (2007).

We begin by assessing the impact of our mass ratio criterion of $0.1 < M_1/M_2 < 10$ by considering sub-samples of galaxy pairs with different stellar mass ratios. For each mass cut, the matching of the control sample in stellar mass and redshift is repeated as described in Section 2 for our fiducial (wide) pairs sample. This ensures that the distribution of stellar masses is comparable between each pairs’ sub-sample and its control sample. In Figure 4, we show the SFR as a function of separation for three different mass ranges (stellar mass ratios within 1:10, 1:3, and 1:2). From this Figure we draw two conclusions. First, the enhancement in SFR persists out to at least $30 \, h_{70}^{-1}$ kpc for all three mass ranges considered, with the closer stellar mass ratio pairs showing an increase out to $40 \, h_{70}^{-1}$ kpc. Second, and perhaps more interesting, is that the amount of SFR enhancement increases (and becomes more significant) for pairs whose stellar masses are most similar to one another.

The enhancement, which we found in the previous subsection to be $40\%$ for pairs with stellar mass ratios within 1:10, increases to 60% and 70% for ratios within 3:1 and 2:1, respectively, and with $\sim 2\sigma$ significance in each case. This confirms quantitatively the suggestion that major interactions, i.e., those between almost equal mass galaxies, will induce the most significant effects in one another. These results also demonstrate that the SFR can be affected even in samples with relatively discrepant masses, at least up to a ratio of 1:10 (as also concluded by Woods & Geller 2007 for their minor pairs). At large separations ($r_p \gtrsim 50 \, h_{70}^{-1}$ kpc) we see an upturn in the SFR of the pairs. This is a complex effect that is driven by a combination of contamination from projected pairs that are not truly interacting and the way in which our control sample is constructed. Since the control sample has been culled in redshift and mass in order to match the distribution in the pairs sample, it is not representative of the true field population. Since pairs tend to be found in higher density environments (Barton et al. 2007), the mass-matched control sample has a higher mean stellar mass than the field (i.e., the pre-cull control sample). In turn, this means that the control sample galaxies are themselves biased toward denser environments and are therefore likely to have, on average, lower SFRs than the field. At wide separations, an increasing number of pairs are not truly interacting, leading to an increased contamination of the sample. The SFRs at these wide separations are therefore averages of the values of true interacting pairs (which at wide separations probably have SFRs tending toward the control mean) and contaminating field galaxies (which tend to have higher SFRs than the control mean). This leads to an apparent upturn in the SFRs at wide separations. The prominence of this upturn will depend on the actual mass matching of each mass ratio sub-sample. Since the $0.1 < M_1/M_2 < 10$ mass-matched control sample is most similar to the field sample (i.e., mass distribution of the pre-cull control sample), the upturn is much smaller (in fact, absent) than in the $0.5 < M_1/M_2 < 2$ mass-matched control sample, which is most discrepant from the field mass distribution. This explains why the majority of previous surveys have not seen this upturn: they do not impose relative flux or mass cuts, hence their SFR versus separation correlations most closely approximate to the top panel of Figure 4. For example, Lambas et al. (2003) see an upturn at $r_p > 60 \, h_{70}^{-1}$ kpc for their $L_1 \sim L_2$ sample, but not in their $L_1 \gg L_2$ sample. Nonetheless, an upturn such as that seen in the middle and bottom panels of Figure 4 has been reported by Perez et al. (2006a) in their analysis of mock galaxy pair catalogs from cosmological simulations, by Nikolic et al. (2004) in their study of SDSS pairs, and, as mentioned above, by Lambas et al. (2003). We conclude that in the absence of projection effects, the SFR of pairs with $r_p > 50 \, h_{70}^{-1}$ kpc would tend to the control value.

Next, we classify major pairs as those with mass ratios within 2:1 and minor pairs as those with more discrepant masses. We further distinguish between the more massive galaxy in a minor pair ($M_{gal}/M_{companion} > 2$) and the less massive galaxy in a minor pair ($M_{gal}/M_{companion} < 0.5$). Since a number of fundamental galaxy properties such as SFR depend on stellar mass (Brinchmann et al. 2004), simply using the matched control sample for comparison with minor/major pairs (whose mass distributions will be very different from one another) would not give a true indication of relative effects. We have therefore further adapted our control samples to be equivalent in mass distribution by selecting a control galaxy matched in stellar mass to each paired galaxy.

In Figure 5 we show the total SFR as a function of galaxy pair separation for three stellar mass scenarios: major pairs and the more/less massive galaxies in minor pairs. In the top panels we show individual SFRs, and in the middle panel the median values in bins of $13 \, h_{70}^{-1}$ kpc. The shaded region in the middle panel shows the median SFR (with vertical height corresponding to the $\sigma/\sqrt{N}$) in the matched control sample. The overlap of the scatter in the data points (vertical error bars on the binned values) with the gray bar gives an indication of consistency with field values. In the lower panel we show the SFR enhancement relative to the control sample by normalizing each bin to the field values. In the lower panel we show the SFR enhancement for cosmic metal enrichment: whereas low-mass galaxies can have a similar conclusion has been drawn by Woods & Geller (2007). Although some of the binned SDSS data points for the more massive galaxy in a pair are also above the field mean, the size of the error bars makes this result less significant (barely 1$\sigma$) and difficult to draw conclusions from. If confirmed, these results would be consistent with the less massive pair member in an unequal mass interaction being susceptible to enhanced star formation, although less so than galaxies in equal mass interactions. In turn, this result has interesting implications for cosmic metal enrichment: whereas low-mass galaxies can

---

6 This is different to the definition of Woods & Geller (2007) who considered the major/minor boundary as a 2 mag difference (factor 6.25) in brightness.

7 Whilst the specific SFR is higher for lower-mass galaxies (Brinchmann et al. 2004) the total SFR is higher for higher-mass galaxies.
usually remain gas rich because of low star-formation efficiency, strong bursts of star formation during interaction may increase metal production which may be more easily dispersed into the surrounding intergalactic medium. However, the results from this section are inconclusive and the analysis of Woods & Geller (2007) remains the strongest evidence for enhanced star formation in less massive galaxies in minor pairs. In a complementary study of star-forming galaxies in the SDSS, Li et al. (2008a) have also recently found evidence that SFRs are more enhanced in lower-mass galaxies with companions. Possible reasons that we have not found similarly significant results include (1) the different definition of major and minor pairs and (2) the smaller sample size of our work, mostly due to the criteria imposed in Section 2 (although Woods & Geller 2007 use the somewhat larger DR5, compared to our DR4 sample). The major pairs sample of Woods & Geller (2007) is 60% larger than ours, whilst the minor pairs sample contains almost twice the number of galaxies. The median luminosity ratio for the Woods & Geller minor sample is ~11 (compared with a median mass ratio of 3.85 in our sample) and ~4 for the major sample (compared with our median major mass ratio of 1.38). Therefore, if the luminosity ratio were taken as a substitute for mass ratio, more than half of the Woods & Geller (2007) major pairs sample would fall into our definition of a minor pair. In future work, it will be interesting to examine how selection based on relative stellar masses and luminosities (e.g., Figure 3) and the definition of major and minor pairs may affect results.

Our data confirm the conclusion of previous work (e.g., Barton et al. 2000; Lambas et al. 2003; Alonso et al. 2004; Nikolic et al. 2004; Li et al. 2008a) that galaxies in pairs closer than ~30 h_{70}^{-1} kpc exhibit SFRs that are higher than in the “field.” For the rest of this paper, we therefore define a sample of “close pairs” where r_p < 30 h_{70}^{-1} kpc. Although we have shown that approximately equal stellar mass pairs show higher proximity-induced SFRs, we elect to use the 0.1 < M_1/M_2 < 10 sample in order to maximize the statistical significance of our work. This selection also facilitates comparisons with previous works, which generally do not have relative stellar mass or flux limits in their pairs selection. The r_p < 30 h_{70}^{-1} kpc, ∆v < 500 km s^{-1}, and 0.1 < M_1/M_2 < 10 criteria now form our fiducial pairs sample unless otherwise stated. The merging timescale for these galaxies is ~250–500 Myr (e.g., Patton et al. 2000; Masjedi et al. 2006).
4. METALLICITIES OF GALAXY PAIRS

In the previous section, we used SFR as a function of separation to define a “close pairs” sample with \( r_p < 30 \, h_7^{-1} \) kpc as those pairs most likely to exhibit interaction-induced effects. We now use this sample to investigate the impact of proximity on galaxy metallicity using this close pairs sample.

The metallicities of the SDSS galaxies can be determined using strong emission line diagnostics that are calibrated either empirically against “direct” electron temperature determinations, or against theoretical photoionization models. A wide range of such metallicity diagnostics is currently on the market; some of the most popular include various empirical calibrations of \( R_{23} \) originally formulated by Pagel et al. (1979) (e.g., McGaugh 1991; Zaritsky et al. 1994), empirical [N II]/H\( \alpha \) calibrations (e.g., Demicoloi et al. 2002; Pettini & Pagel 2004), and calibrations which solve iteratively for ionization parameter using photoionization models (e.g., Kewley & Dopita 2002; Kobulnicky & Kewley 2004). It is well known that at high metallicities these strong line diagnostics show a positive offset relative to the metallicities determined from electron temperature methods (e.g., Bresolin et al. 2004; Bresolin 2007). Moreover, Kewley \& Ellison (2008) have shown that strong, systematic differences exist between strong line diagnostics and have stressed the importance of using a single calibration where possible. In this paper, we use the Kewley \& Dopita (2002) “recommended” method which can both overcome the usual double-value degeneracy of the \( R_{23} \) method and also solves for the ionization parameter.

As noted in Section 2, the (necessary) selection of galaxies with strong emission lines means that our sample contains a dearth of metal-poor galaxies. However, not only does the consistent selection of control and paired galaxies ensure an internally fair comparison, but repeating our analysis with less stringent emission line detection constraints (3\( \sigma \) rather than 5\( \sigma \)) yields identical results for all of the tests performed in this section.

4.1. The Luminosity–Metallicity Relation

The relationship between luminosity and metallicity is well established over 8 mag in \( M_B \) (e.g. Salzer et al. 2005; Lee et al. 2006) and out to redshifts \( z \sim 1 \) (e.g., Kobulnicky \& Kewley 2004; Maior et al. 2005). The reason for the LZ relation and the tighter MZ relation is still unclear. Although yields from luminous, high-mass galaxies indicate that the relation is driven by the depth of the potential well and mass loss during star formation (Tremonti et al. 2004), lower-mass galaxies show a large scatter in effective yield, with some showing values as high as the most massive galaxies (Lee et al. 2006). Simulations of chemical evolution offer a variety of alternatives, including variable initial mass functions (Koppens et al. 2007), star-formation efficiency (Brooks et al. 2007), and the interplay between metal-poor gas inflow and mass-loaded winds (Finlator \& Davé 2008). Ellison et al. (2008) have recently shown that the normalization of the MZ relation depends on specific SFR and \( r_p \) and conclude that differences in star-formation efficiencies can explain these dependences. However, the basic form of the relation remains intact over the full range in these properties and apparently does not depend sensitively on large-scale environment (Mouchine et al. 2007).

Regardless of the origin of the LZ relation, the enhanced star formation discussed in the previous section should ultimately impact on the correlation of luminosity and metallicity in close galaxy pairs. The direction of this impact is dependent on timescales. If a galaxy’s metallicity is measured after an interaction-driven starburst is complete, then we may expect an enhanced metallicity in the H\( \alpha \) regions where star formation has occurred. Conversely, if we measure the metallicity of the region experiencing the starburst whilst it is ongoing, the inflow of more metal-poor gas from the outer regions of the galaxy may decrease the H\( \alpha \) region metallicity. Shifts in luminosity may also be applicable due to enhanced star formation. This question has been recently tackled by Kewley et al. (2006a) who used 86 galaxies in pairs selected from the CfA2 redshift survey and compared them with a control sample from the Nearby Field Galaxy Survey (NFGS). For both samples, nuclear spectra containing \( \sim 10\% \) of the galaxy’s light were used for the metallicity determinations. Kewley et al. (2006a) found that galaxies with separations \(< 30 \, h_7^{-1} \) kpc have metallicities that are offset downward by 0.2 dex at a given luminosity. Further observational evidence that merger-induced starbursts lead to lower metallicities comes from studies of ultra-luminous infrared galaxies (ULIRGs; Rupke et al. 2008) and compact ultraviolet luminous galaxies (UVLGs; Hoopes et al. 2007). These populations, believed to have been recently involved in merger events, are more metal-poor by up to a factor of 2 compared to SDSS galaxies of the same mass. The simulations of Perez et al. (2006b) also support the concept of metal-poor gas inflow in pairs. They find that the gas phase metallicity of galaxies in simulated pairs is typically 0.2 dex higher when the integrated metallicity over 2 optical radii is compared to that over half an optical radius.

In Figure 6, we show the LZ relation for our SDSS samples of pairs and control galaxies. In the top left panel we show all galaxies in our close pairs sample, i.e., with transverse projected separations \( r_p < 30 \, h_7^{-1} \) kpc. Kewley et al. (2006a) have argued that offsets from the field LZ relation will be most clear when the spectra are of a nuclear nature, i.e., only cover the central few kpc of the galaxy where the starburst is occurring. We therefore plot the LZ relation for three different CF cuts. In order to make any offsets between the field and pairs more clear, in Figure 7, we show binned versions of all the SDSS pairs, as well as for the various CF cuts. We note that due to the exclusion of very metal-poor galaxies in our sample, it is possible that any downward shift in metallicity in the pairs sample is underestimated. For comparison, we also show the Kewley et al. (2006a) CfA pairs sample and their NFGS control sample, both as individual galaxies and binned. The visual impression that the CfA pairs of Kewley et al. (2006a) have lower metallicities for their luminosity than NFGS control galaxies is confirmed quantitatively with a 2D KS test which shows that the LZ distribution of the two samples differs at the 98\% confidence level.

If we consider the SDSS sample as a whole (top left panels of Figures 6 and 7), we see a mild tendency toward lower metallicities for pairs compared with the control sample. However, the offset is small, \(< 0.05 \) dex, compared to the offset seen by Kewley et al. (2006a), which is typically 0.1–0.2 dex. The main difference between the SDSS sample and the NFGS/CfA sample studied by Kewley et al. (2006a) is that the latter had nuclear spectra with CF \( \sim 10\% \). The majority of the SDSS galaxies have much higher CFs (Figure 2). If

---

8 We have converted the separations used by Kewley et al., who quote distances in units of \( h_100^{-1} \) kpc, to our cosmology and convention of \( h_7^{-1} \) kpc.
the effect observed by Kewley et al. (2006a) is therefore truly nuclear, then the typically higher CFs of the SDSS fibers may hide the impact of gas dilution in the galaxies’ centers. It would therefore be more appropriate to consider only the SDSS galaxies (in both pairs and control sample) with CF < 10%. The top right panels in Figures 6 and 7 show the individual galaxies and binned metallicities for the CF < 10% criterion. Although our sample of CF < 10% pairs is smaller than the CfA (23 galaxies, compared with 37 in the CfA), the scatter in metallicity is also smaller for a given MB, leading to smaller error bars (which represent the standard error on the mean).

The SDSS CF < 10% control sample is also much larger than the NFGS: 2060 galaxies compared with 43 at comparable separations. Figure 7 therefore shows the interesting result that, at least for intermediate luminosity galaxies, SDSS pairs with CF < 10% have marginally higher metallicities for their luminosity than the control sample. Recall that this offset is in the opposite sense to the CfA pairs studied by Kewley et al. (2006a). A 2D KS test gives a 3% probability that the SDSS control and pairs sample have the same LZ distributions. As stated above, the KS probability is 2% for the Kewley et al. samples, so both datasets give statistically significant results, but in contrary directions. It is worth noting that the CFs for the CfA and SDSS samples are calculated slightly differently: Kewley et al. consider the fraction of light in the slit relative to the B26 isophote, whereas we consider the fiber magnitude relative to the Petrosian magnitude in the g-band. However, this cannot explain the trend of our result, i.e., that we see a larger offset in the pairs’ LZ relation relative to the control for higher CFs, which is contrary to the expectation from nuclear metallicity dilution.

4.2. Comparison with the Work of Kewley et al. (2006a)

The results in the previous subsection indicate an apparent discrepancy in the relative metallicities of galaxy pairs in the SDSS versus the CfA samples for nuclear (CF < 10%) spectra. On the one hand, Kewley et al. (2006a) find low metallicities at a given luminosity in close pairs, whereas we find tentative evidence for high metallicities compared with a control sample when the CF < 10%. Conversely, we do find lower metallicities in pairs when the CF > 20% (Figure 7), a regime in which Kewley et al. (2006a) have little data. In this subsection, we investigate the cause of this apparent discrepancy.

First, we consider whether the small number of low CF galaxies in the SDSS (23, versus 37 in the CfA) could lead to disagreement relative to the nuclear LZ relation of Kewley et al. (2006a). We quantify the effect of small number statistics by bootstrapping 10,000 samples of 23 galaxy pairs from the CfA sample and calculating the 2D KS probability compared with the NFGS control sample. This test simulates the effects of the smaller number of pairs in the SDSS compared with the CfA, i.e. by testing whether the CfA/NFGS comparison would have detected an LZ offset if it had only had as many pair galaxies as the small CF bin of the SDSS. We find that for samples of 23 pairs a significant KS probability of <0.05 is achieved in 86% of the bootstrap renditions and a probability of <0.02 for 63% of trials. Therefore, although we cannot completely rule out the possibility that small numbers are the cause of the apparent discrepancy between the SDSS and CfA nuclear LZ relation for pairs, it seems unlikely.

We next consider whether there any obvious differences between the selection of Kewley et al. (2006a) and our samples.
Both works rely on pair identification from transverse (projected) separation and relative velocity. We have selected our close pairs sample $r_p < 30 \, h^{-1}_{70} \, \text{kpc}$ to match the closest separation bin of Kewley et al. (2006a). Our velocity cut is somewhat more stringent than Kewley et al., 500 km s$^{-1}$ rather than 1000 km s$^{-1}$. However, repeating the LZ and MZ analyses with a 1000 km s$^{-1}$ cut for the SDSS pairs does not change our results (increasing the velocity range only increases our pairs sample by 7%). The CfA pairs sample has a lower-redshift range than the SDSS, the former having a lower-redshift cut-off of $z = 0.0077$ and a median redshift of $z = 0.018$, which is close to the low $z$ cut-off in the SDSS. However, we consider it unlikely that evolutionary effects can be significant over the redshift ranges covered by the two surveys. Ellison & Kewley (2005) and Kewley & Ellison (2008) have also stressed the importance of using the same metallicity diagnostics in comparisons, since there can be a factor of 3 offset for different calibrations. Both Kewley et al. (2006a) and our work use the Kewley & Dopita (2002) “recommended” metallicity calibration, so there should be no offset due to diagnostic differences. At this point, it is instructive to compare the two control samples of this work and Kewley et al. (2006a). Although the selection of the CfA sample is done in the $B$-band, as opposed to the $r$-band selection of SDSS pairs, Figure 8 shows that a similar range in $M_B$ is probed by both samples (although the latter extends to slightly more extreme values at both ends of the $M_B$ distribution, thanks to the larger sample). Figure 8 also shows that, despite our caveat in Section 2 that we may be missing low metallicity galaxies, the
SDSS sample is not deficient in sub-solar abundance galaxies compared with the CfA. Nonetheless, from Figure 8 it is clear that the NFGS control galaxies are inconsistent with the SDSS control; a 2D KS test rules out the null hypothesis with 99.8% confidence. Therefore, despite apparently similar selection in terms of redshift, projected separation, $\Delta v$, metallicity diagnostic, and CF, the LZ distributions of NFGS and SDSS control samples are significantly different.

A possible clue as to the origin of the difference between the CfA/NFGS and SDSS samples is revealed by the trend in LZ offset with CF seen in Figure 7. Although the SDSS pairs show mildly enhanced metallicities for CF $< 10\%$, for $10 < CF < 20\%$ there is no offset compared with the control, but at $20 < CF < 50\%$ the pairs are systematically more metal poor. Since CF will obviously be a strong function of galaxy half light radius, so the trend in LZ offset with CF might actually be a trend in galaxy size. If confirmed, this would imply that galaxies with smaller $r_h$ tend to have low metallicities for their luminosity, whereas larger galaxies may be offset in the opposite direction. In Figure 9, we compare the $r_h$ distributions of the CfA pairs with the SDSS pairs with two CF cuts: CF $< 10\%$ and $20 < CF < 50\%$. The histogram clearly shows that the CfA pairs have a $r_h$ distribution that is skewed toward smaller sizes than the SDSS CF $< 10\%$ pairs. Therefore, although these two samples have similar CFs, the size distribution of galaxies is very different. On the other hand, the SDSS $20 < CF < 50\%$ and CfA pairs have very similar $r_h$ distributions. In turn, the LZ relations of these two samples (CfA pairs and SDSS pairs with $20 < CF < 50\%$) show concordantly low metallicities for a given luminosity. We can see this explicitly in Figure 10 where we plot the LZ relation for different half light radii; galaxies with $r_h < 3 h_{70}^{-1}$ kpc are metal deficient for their luminosity, but this effect is absent for larger galaxies. The small enhancement in metallicity that was present for small CFs in Figure 7 is absent for the large $r_h$ sub-sample in Figure 10. This may be due to the fact that nuclear spectra are required to see the effect, i.e. the galaxies need to be large and the spectra must have small CFs. Our sample is not large enough to test this hypothesis, but it would be clearly interesting to obtain more nuclear spectra of galaxies with $r_h > 6 h_{70}^{-1}$ kpc in the future. Finally, the results shown in Figures 7 and 10 also demonstrate that the impact of low metallicity gas inflow is seen not only in the CF $\sim 10\%$ nuclear spectra of the CfA pairs, but also in the larger CFs of the SDSS pairs. This indicates that the offset in the LZ relation may be driven by changes that occur on scales larger than “nuclear.” There are (at least) two reasons why this might be the case. First, we may be observing the galaxies early enough in their interaction that the gas flows are still ongoing, i.e. the metal-poor gas is still on its way to the center. This would imply that the offset in the LZ plane on scales of several kpc is highly transient. Alternatively, galaxy interactions, which are thought to enhance star formation (Gerin et al. 1990) and contribute to central gas flows (Friedli & Benz 1993), may result in galaxies with flatter abundance gradients (Martin & Roy 1994). Combined with the transport of metal-poor gas to the center, this could result in a longer lasting suppression of the LZ relation in some galaxy pairs. We return to the reason for the offset in the LZ relation in Section 4.4.

4.3. The Mass–Metallicity Relation

We repeat the analysis of the previous section, but now replace luminosity with stellar mass. In Figure 11, we show the MZ relation for our control and close pairs samples for different cuts in CF. Comparison with Figure 6 highlights the result of Tremonti et al. (2004) that the MZ relation is much tighter than the LZ relation, with a 1σ spread $<0.2$ dex for a given stellar mass. In Figure 12, we show the binned MZ relation for close pairs and control samples for all the SDSS galaxies as well as for the three CF cuts. Although there is a slight tendency toward marginally lower metallicities for a given mass in the full pairs sample, as seen in the binned LZ relation, the shift is again $<0.05$ dex and not significant given the error bars. However, the CF $< 10\%$ sample again shows a significant enhancement in metallicity at intermediate masses. The KS probability that the MZ distributions of the CF $< 10\%$ pair and control samples being drawn from the same population is 2%, i.e. as significant as the LZ result for the CfA sample (Kewley et al. 2006a) and slightly more significant than the LZ result for the SDSS pairs presented above. We see a similar trend in the offset in metallicities as a function of CF in the MZ relation as in the LZ relation—an increase in metallicity for small CFs and lower metallicities for pairs with high CF spectra. However, although the offset toward lower metallicities in the $20 < CF < 50\%$ CF bin is systematic in MZ, it is slightly less statistically significant than in LZ. Whereas the offset in the LZ relation for $20 < CF < 50\%$ is $0.05–0.1$ dex, with the largest offsets at the lowest luminosities, the offset in MZ is consistently around 0.05 dex. This indicates that the brightest galaxies ($M_h < -20$) may be exhibiting a pure metallicity shift. This is perhaps not surprising since a starburst of fixed luminosity will have a fractionally small impact on the
luminosity of an intrinsically bright galaxy. Moreover, the flat slope of the LZ relation at bright magnitudes means that any luminosity shift will need to be large in order to be detected. However, if the metallicity shift is about 0.05 dex downward for all luminosities/masses (as indicated in Figure 12), there may be an additional luminosity component to the LZ relations shift that contributes up to \(\sim 0.4\) mag.

Kewley et al. (2006a) argued that the offset observed in the LZ relation determined for their CfA pairs sample was driven by a difference in metallicity rather than luminosity. Their argument was based on the fact that their absolute magnitudes were derived from the \(r\)-band where new star formation will contribute little continuum flux. Barton et al. (2001) also concluded that triggered star formation will not significantly increase the luminosity of a paired galaxy, based on comparisons of the Tully–Fisher relation. However, the marginally larger offset that we find in the LZ relation determined at \(M_B > -20\), compared to the MZ relation for a given CF, raises the question as to whether some of the shift may be due to an increased luminosity in pairs, as well as a lower metallicity. Although there is little continuum flux expected from a starburst in the \(r\)-band, the \(H\alpha\) line is present in this bandpass and may contribute significantly. To test whether the shift in the LZ relation may be due to increased luminosity in close galaxy pairs, we calculate the absolute magnitude in four SDSS filters \((u, g, r, \text{ and } i)\) and use these magnitudes in the LZ relation. If an increase in luminosity from a central starburst is shifting the LZ relation of pairs toward brighter absolute magnitudes, we expect to see this effect more strongly in the blue filters.

In Figure 13, we show the LZ relation derived for \(20 < CF < 50\%\) for SDSS control and pairs samples for absolute magnitudes in four filters. We first note that the LZ relation is much flatter for bluer filters, an effect particularly noticeable in the \(u\)-band. This is probably due to the high sensitivity of the \(u\)-band magnitude to instantaneous star formation which smears out the underlying relation of metallicity with mass. The correlation of the \(i\)-band magnitude with metallicity very closely resembles the MZ relation since redder filters more faithfully represent the underlying stellar mass. Figure 13 shows that the horizontal shift in the linear (fainter absolute magnitude) part of the LZ relation is shifted marginally more in the \(u\)-band filter \((\sim 0.75\) mag) than in the other filters \((\sim 0.6\) mag). Combined with the smaller shift in the MZ relation, this indicates that part of the overall shift of pairs relative to control galaxies in the LZ relation may be due to the brightening of pairs experiencing a starburst. This idea is further supported by the brighter median \(M_B\) in the close pairs sample: \(-20.15\) compared with \(-19.94\) for the control galaxies. Recall that the two samples are well matched in mass (see Figure 2), so that this difference in absolute magnitude is likely associated with the additional star formation in pairs.
found in Section 3. Shioya et al. (2004) model the change in absolute magnitude in starbursting mergers and predict a total brightening of $\sim$1 magnitude in $M_B$. However, fading happens rapidly and a brightening of a few tenths of a magnitude is commensurate with a time of only a few hundred million years after the burst.

4.4. On the Shift in the LZ/MZ Relations

The results in the previous sections, and shown in Figures 7 and 12, hint that the magnitude and direction of the offset in the LZ/MZ relations is a function of CF. We have also shown that the dependence on CF is a manifestation of a strong empirical dependence on the intrinsic galaxy half-light radius. Ellison et al. (2008) have shown that a segregation in the MZ relation exists even within the control sample of galaxies. However, in the control sample of non-paired galaxies used by Ellison et al. (2008) there is a shift toward lower metallicities for larger radii. In the pairs sample, it is the galaxies with the smallest half-light radii that show lower metallicities for a given mass. The mechanism for the metallicity shift in pairs is therefore likely to be driven by a different physical cause. Based on qualitatively similar downward shifts in metallicity for a given stellar mass in ULIRGs and compact UVLGS (Rupke et al. 2008; Hoopes et al. 2007), but the absence of a significant dependence on large-scale environment (Mouhcine et al. 2007), it is likely that this effect is due to merger activity. In this subsection, we explore two possible “fundamental” parameters that may be the underlying cause of the $r_h$ dependence of the MZ relation for paired galaxies.

4.4.1. Dynamical Time

Finlator & Davé (2008) have recently proposed a general model (i.e., not specific to galaxy pairs) for the existence and form of the MZ relation. These authors suggest that the MZ (and by association, the LZ) relation can be understood via the interplay of gas accretion from the intergalactic medium, star formation, and subsequent mass loss through winds. In this model, there is an equilibrium metallicity for a galaxy of a given mass from which the galaxy may be displaced by the inflow of metal-poor material. In response to the deposition of fresh fuel, which in turn increases the gas surface density, the galaxy will experience an increase in its SFR. A key parameter in this model is the ratio of the galaxy’s dynamical time ($t_{dyn}$) and the dilution time ($t_d$). The dilution time is defined as the time taken for the galaxy to recover from the injection of metal-poor gas and return to its equilibrium metallicity. If $t_d < t_{dyn}$, then the galaxy “recovers” its equilibrium metallicity promptly, leading to very little scatter in the MZ relation. Conversely, if $t_d > t_{dyn}$, then the galaxy struggles to recover promptly from inflows. In Figure 14, we test the effect of $t_{dyn}$ in the normalization of the LZ relation by splitting the pairs and control galaxies by dynamical time, which we calculate from $r_h$ and stellar mass. For short dynamical
times, we find a tendency for pairs to have low metallicities for their luminosity. This could be understood, in the context of the model described above, if galaxies with short $t_{\text{dyn}}$ are those that most efficiently funnel metal-poor gas. However, it is then difficult to explain why galaxies with longer dynamical times should have metallicities higher than the control sample. Enhanced metallicities might be associated with induced star formation that has already deposited its metals back into the ISM, but this is unexpected for long $t_{\text{dyn}}$, which should have less prompt induced star formation than galaxies with short $t_{\text{dyn}}$. We therefore conclude that dynamical time is unlikely to be the fundamental parameter driving the sensitivity of the LZ in pairs to $r_h$. This is perhaps not surprising given that the gas accretion in the “field” galaxies simulated by Finlator & Davé (2008) occurs via a very different mode than the infall of gas to the nucleus of a paired galaxy. That is the former is dependent on the free-fall time of gas from the intergalactic medium, whereas the latter requires funneling of gas to the center that is already settled in the outer part of the galactic disk.

4.4.2. Bulge Fraction

The segregation of the galaxy pair LZ/MZ empirically depends on $r_h$. Galaxies with smaller sizes for a given mass will have a higher-mass density, whereas galaxies with larger $r_h$ and the same mass will have shallower mass potentials. We therefore next consider whether it is the spatial mass distribution in galaxies that drives the offset in the LZ and MZ relations of paired galaxies. Simulations of galaxy interactions have previously shown that one of the factors that regulates gas inflow and nuclear starbursts is the relative prominence of the galaxy’s bulge (e.g., Mihos & Hernquist 1994, 1996; Cox et al. 2008). Bulges appear to provide stability against gas inflow, so that galaxies with low bulge fractions more efficiently funnel gas to their centers. We therefore investigate whether bulge fraction may be driving the different offsets in the LZ/MZ relations for different galaxy half light radii.

In Figure 15, we show the histogram of $i$-band bulge-to-total ($B/T$) ratios for galaxies with close companions. We chose the $i$-band for this comparison since the $B/T$ fractions measured in blue filters may primarily measure any increase in nuclear star formation (e.g. Paper II). The $i$-band is selected to be a good indicator of the underlying mass distribution between the bulge and the disk. In Figure 15, we have further divided the close pairs sample into those galaxies which have small half light radii, $r_h < 3 h_{70}^{-1}$ kpc, and those with larger sizes. Figure 15 shows that small $r_h$ galaxies in close pairs tend to have higher bulge fractions than large galaxies. The KS probability that the two distributions are the same is 0.007.

Figure 15 shows a potential link between $r_h$ and $B/T$. Cox et al. (2008) have suggested that galaxies in unequal mass mergers with $B/T > 0.3$ will have burst efficiencies three times lower than a bulgeless galaxy in an otherwise identical interaction. Paired galaxies with $r_h < 3 h_{70}^{-1}$ kpc appear to have a marked dearth of bulge fractions below this value, indicating that small galaxies may be less efficient at funneling gas to their centers for star formation. A possible explanation for the offsets in the LZ relation seen in Figure 7 may therefore be the connection between galaxy size and typical bulge fraction. Indeed, dividing the galaxy samples by $B/T$ does show an LZ.

---

9 Cox et al. (2008) deal with bulge-to-disk ratios, which we convert to $B/T$ for consistency.
offset for large, but not small, bulge fractions (see Figure 14). This can be explained if smaller galaxies ($r_h < 3 h^{-1}_{70}$ kpc), which tend to have $B/T > 0.3$ (see Figure 15), have their metal-poor gas reservoirs disrupted in an interaction, leading to an overall injection of metal-poor gas into the central $\sim 5-10 h^{-1}_{70}$ kpc. However, this gas is not efficiently funneled into the very center of the galaxy, leading to less efficient star formation and overall lower gas metallicity extending over a projected area of several kpc. Although this gas may eventually experience a starburst, Cox et al. (2008) have shown that this event is delayed relative to the initial (first passage) starburst by $\sim 1$ Gyr. Larger galaxies, which are more likely to have $B/T < 0.3$, more efficiently funnel gas to their centers, leading to a prompt nuclear starburst and rapid metal enrichment and recovery to metallicity levels commensurate with the control sample (Figure 14).

To further test this hypothesis, in Figure 16 we plot the bulge $g - r$ colors for three cuts in $B/T$, where the cuts are applied to both the control and pairs samples. We find that the galaxies with the smallest bulge fractions ($B/T < 0.3$) have no difference in $g - r$ color, compared to 0.31 and 0.18 for $0.3 < B/T < 0.6$ and $B/T > 0.6$, respectively. Indeed, the distribution of $g - r$ colors for the lowest bulge fraction galaxies is actually consistent (KS probability = 0.19) between the control sample and the pairs. The key to interpreting this result is relative timescales: that of color changes following a starburst versus interaction timescales. The scenario described above, in which $r_h$ depends on $B/T$, the latter parameter being a determining factor in the efficiency of nuclear star formation, could explain the $g - r$ distributions of Figure 16 if the timescale for post-starburst color changes is shorter than, or comparable to, the dynamical time of the pair. Bruzual & Charlot (1993) show that for a $10^7$ year burst of star formation, the optical colors evolve most rapidly over the first $10^8$ years after the starburst. After this point, both the models and actual star cluster data show a relative plateau in color, changing by less than 0.1 mag in $B - V$ up to 1 Gyr. Moreover, the fading of a starburst is typically a few magnitudes from $10^7-10^8$ years after the burst, after which it will usually be barely visible on top of the continuous, ambient star-forming galaxy population (M. Sawicki 2007, private communication), although the exact contrast will of course depend on the relative strength of the starburst. The typical dynamical time of close pairs is of the order of a few hundred Myr to half a Gyr (Mihos & Hernquist 1996; Barton et al. 2000; Patton et al. 2000). We therefore speculate that one explanation of our observations is that many of the close pairs in our sample have already experienced gas disruption from an initial pass $\sim 10^8$ yr ago. In the larger galaxies (which have a tendency toward smaller bulge fractions) this has resulted in a prompt nuclear starburst and metal enrichment leading to high metallicities for a given luminosity compared with the field, but a stellar population that has already lost its massive O and B stars. In the smaller galaxies, the re-distribution of metal-poor gas has led to a lower metallicity for a given luminosity compared with the field. In these bulge-dominated galaxies, star formation still
occurs, but is delayed relative to the first passage (Cox et al. 2008), so we still see the evidence of ongoing activity in their colors.

5. AGN FRACTION

There is strong observational and theoretical evidence linking the interactions of galaxies and the onset of nuclear activity. Storchi-Bergmann et al. (2001) found a correlation between central star-formation activity and AGN in interacting galaxies, providing a causal link between the two processes. This observation was confirmed by Kauffmann et al. (2003a) who found that the star formation in AGN-dominated galaxies is distributed over the central few kpc of active galaxies. Kauffmann et al. (2003a) also found that a larger fraction of AGN galaxies (as opposed to non-active massive galaxies) have experienced significant bursts of star formation in the past few Gyr. Alonso et al. (2007) draw a similar conclusion, based on lower values of the break index $D_{b}(4000)$ which indicates more recent star formation in visibly merging galaxies with AGN activity. In the previous sections, we have presented evidence for central starburst activity in close galaxy pairs; do we see any evidence for enhanced AGN activity in our pairs that has followed the starburst?

To investigate this question, we remove the criterion that galaxies must be classified as H$_{II}$ (star-forming) galaxies and also include those that have been classified as dominated by an AGN ionizing spectrum. The classification of galaxies as star-forming or AGN-dominated can be achieved with a variety of line strength diagnostics; in this work we use the diagnostic of Kewley et al. (2001). This leads to an approximate 10% increase in the size of our pairs and control samples. However, we impose the criterion that the bulge-to-total ratio be in the range $0 < B/T < 1$, i.e. that the galaxy is fitted with two components and excludes pure disks and pure bulges, which significantly reduces the number of galaxies considered. Furthermore, although our main pairs sample is still defined as containing galaxies with companions whose separations lie in the range $r < 30 h_{70}^{-1}$ kpc, we also consider a wide pairs sample of galaxies whose companions have separations $30 < r < 80 h_{70}^{-1}$ kpc. The wide pairs sample acts as a consistency check, since any differences due to proximity should be weaker in the wide pairs sample than the sample of close pairs. A summary of the numbers of galaxies in the various samples considered in this section is given in Table 1.

We now examine the fraction of galaxies in the pairs versus control sample which are classified as AGN as a function of color, $B/T$, and smoothness; our results are given in Table 1. The smoothness parameter, $S$, is derived from the GIM2D bulge-disk fits as described in detail by Simard et al. (2002). In brief, $S$ measures both the smoothness of the disk+bulge
Table 1
AGN Fractions

| Selection criteria | Number of galaxies | AGN fraction |
|--------------------|--------------------|--------------|
| | Control | Wide pairs | Close pairs | Control | Wide pairs | Close pairs |
| All galaxies | 30025 | 936 | 502 | 0.12 ± 0.01 | 0.14 ± 0.02 | 0.13 ± 0.02 |
| $\log M_* < 10.2 M_\odot$ | 13059 | 432 | 237 | 0.02 ± 0.01 | 0.03 ± 0.01 | 0.00 ± 0.01 |
| $\log M_* \geq 10.2 M_\odot$ | 16993 | 504 | 265 | 0.20 ± 0.01 | 0.24 ± 0.02 | 0.25 ± 0.03 |
| $(g-r)_{\text{bulge}} < 0.8$ | 14644 | 543 | 337 | 0.08 ± 0.01 | 0.09 ± 0.01 | 0.08 ± 0.02 |
| $(g-r)_{\text{bulge}} \geq 0.8$ | 15408 | 393 | 165 | 0.16 ± 0.01 | 0.22 ± 0.02 | 0.24 ± 0.04 |
| $(g-r)_{\text{disk}} < 0.5$ | 14173 | 441 | 257 | 0.04 ± 0.01 | 0.07 ± 0.02 | 0.07 ± 0.02 |
| $(g-r)_{\text{disk}} \geq 0.5$ | 15879 | 495 | 245 | 0.19 ± 0.01 | 0.21 ± 0.02 | 0.20 ± 0.03 |
| $B/T < 0.2$ | 14041 | 388 | 124 | 0.05 ± 0.01 | 0.06 ± 0.02 | 0.07 ± 0.03 |
| $B/T \geq 0.2$ | 16011 | 548 | 378 | 0.18 ± 0.01 | 0.20 ± 0.02 | 0.15 ± 0.02 |
| $S_g < 0.1$ | 18856 | 518 | 213 | 0.15 ± 0.01 | 0.20 ± 0.02 | 0.19 ± 0.03 |
| $S_g \geq 0.1$ | 11196 | 418 | 289 | 0.08 ± 0.01 | 0.07 ± 0.01 | 0.09 ± 0.02 |
| $(g-r)_{\text{bulge}} < 0.8$ | 9614 | 220 | 69 | 0.19 ± 0.01 | 0.29 ± 0.04 | 0.33 ± 0.07 |
| $(g-r)_{\text{bulge}} \geq 0.8$ | 4584 | 105 | 29 | 0.33 ± 0.01 | 0.47 ± 0.07 | 0.52 ± 0.14 |

and its asymmetry with higher values of $S$ indicating a higher degree of asymmetry across the galaxy within two half-light radii. Smoothness is therefore a good indicator of morphology with later type galaxies exhibiting generally higher values of $S$ (McIntosh et al. 2004). Here, we use $S_g$, smoothness as measured in the $g$-band.

In Figure 17, we show the fraction of “all” galaxies (i.e. corresponding to the first line in Table 1) that are AGN as a function of redshift. The control galaxies show a steady increase in AGN fraction with redshift. However, this is likely to be dominated by systematic selection rather than physical effects. Since the stellar mass distribution is strongly skewed to higher values at higher redshifts (see discussion in Section 2) and higher-mass galaxies have higher AGN fractions (lines 2 and 3 in Table 1) it is not surprising that the control galaxies exhibit increasing AGN fraction at higher redshifts.
Conversely, Woods & Geller (2007) find a higher AGN fraction presence of close neighbors does not promote nuclear activity. That although active galaxies with close neighbors show similar a sample of 90,000 AGNs from the SDSS DR4 to demonstrate found that AGN fraction is also independent of environment in beyond galaxy pairs, Miller et al. (2003), and references therein, of non-AGN matched in mass and redshift. Extending this work extra neighbor within 70 kpc compared with a control sample not show proximity-induced effects such as enhanced SFR or wide pairs add as a consistency check because (a) they do not provide any offset in LZ and (b) we know that the wide pairs sample is consistent between the control and the pairs samples. However, the small number of pairs (particularly at high redshift) in each redshift bin means that the uncertainties on AGN fraction are quite high.

The results in Table 1 show that different selection criteria yield different AGN fractions. In general, more massive, redder, elliptical (low $S_e$, high $B/T$) galaxies have a higher AGN fraction than less massive, bluer, spiral galaxies. There are a few selection criteria for which the close pairs have a higher AGN fraction than the control, e.g. $(g - r)_{\text{bulge}} \geq 0.8$. However, in no case do we see a higher AGN fraction for close pairs than for both the wide pairs and the control samples. The wide pairs add as a consistency check because (a) they do not show proximity-induced effects such as enhanced SFR or offset in LZ and (b) we know that the wide pairs sample is likely to be quite highly contaminated (Perez et al. 2006a). The fractions given in Table 1 therefore do not provide any convincing evidence that interactions lead to an increased AGN fraction in close pairs. A similar conclusion was reached by Barton et al. (2000) for their CFA redshift pairs sample. A larger and more recent study by Alonso et al. (2007) draws the same conclusion—the distributions of properties such as color, concentration (analogous to our $B/T$ ratio), or morphology (measured here by $S_e$) are indistinguishable for close pairs and control galaxy samples. These results are consistent with the finding of Li et al. (2006) that only one AGN in 100 has an extra neighbor within 70 kpc compared with a control sample of non-AGN matched in mass and redshift. Extending this work beyond galaxy pairs, Miller et al. (2003), and references therein, found that AGN fraction is also independent of environment in groups and clusters. Most recently, Li et al. (2008b) have used a sample of 90,000 AGNs from the SDSS DR4 to demonstrate that although active galaxies with close neighbors show similar enhancements in star formation as non-AGN galaxies, the presence of close neighbors does not promote nuclear activity. Conversely, Woods & Geller (2007) find a higher AGN fraction in both minor and major pairs compared with field galaxies in a sample of 1200 galaxies with companions in the SDSS DR5. If we had not considered separately the close and wide pairs, and considered the latter as a “secondary control,” we would have drawn an identical conclusion for some of the subsets considered in Table 1. However, our expectation that the wide pairs should approximate to the control sample leads us to reject the significance of the increased AGN fraction in the three cases where it is seen in Table 1.

The typical dynamical and burst timescales of close pairs are typically a few hundred Myr (Mihos & Hernquist 1996; Barton et al. 2000), an order of magnitude shorter than the time-since-burst of the Kauffmann et al. (2003a) AGN sample. Taken together, this paints a picture of delayed AGN activity that begins much later than the initial central starburst. This is also the scenario provided by merger models which show that starbursts in the central regions of galaxies can be seen early in the interaction process. However, accretion rates only increase later when the merging is much more advanced, i.e. after at least a Gyr, and the galaxy has formed a massive elliptical (e.g., Bekki & Noguchi 1994; Di Matteo et al. 2005; Bekki et al. 2006). The simulation results are born out observationally by the work of Alonso et al. (2007) who, having found no distinction in galaxy properties for their pairs/control sample, visually classified the subset of pairs that were clearly interacting or merging. This visual classification led to a clear distinction in the properties of galaxies that were actively merging, rather than those that were simply close in Δv and separation.

6. SUMMARY AND CONCLUSIONS

We have presented a sample of 1716 galaxies with close ($r_p < 80 h^{-1}_7 $ kpc, $Δv < 500$ km s$^{-1}$, and $0.1 < M_1/M_2 < 10$) companions selected from the SDSS DR4, whose properties we have compared with a control sample of 40,095 galaxies. The combination of photometric and spectroscopic data for these galaxies yields a consistent, large sample of properties including metallicity, SFR, mass, $B/T$ ratios, colors, and AGN contribution. Our main conclusions are as follows.

1. SFR and proximity. Galaxy pairs have higher SFRs by up to 70% for separations <40 $h^{-1}_7$ kpc compared with a control sample of galaxies with equal stellar mass distribution. This result is in agreement with inferences from numerous other studies (e.g., Barton et al. 2000; Lambas et al. 2003; Nikolic et al. 2004; Geller et al. 2006) which have measured the enhancement of Hα equivalent width as a function of separation.

2. SFR and relative galactic stellar mass. The enhancement in SFR is largest for galaxies in pairs with mass ratios $0.5 < M_1/M_2 < 2$ and steadily decreases for paired galaxies with more discrepant stellar masses. We find tentative evidence for enhanced SFR in the less massive galaxy of a minor (mass ratio greater than 2:1) pair, but the result is not statistically significant. The (luminosity-selected) pairs study of Woods & Geller (2007) provides the strongest evidence for a more enhanced SFR in the lower-mass galaxy of a pair.

3. Luminosity–metallicity and mass–metallicity relation. We find an offset in the LZ and MZ relations for galaxies in pairs with $r_p < 30 h^{-1}_7$ kpc relative to our control sample. For galaxies with small half light radii ($r_h < 3 h^{-1}_7$ kpc), which tend to be observed with large CFs in the SDSS, we
find a 0.05–0.1 dex offset in the LZ relation toward lower metallicity in the pairs compared with the control. This is consistent with the previous result of Kewley et al. (2006a). A shift is also present in the MZ relation for large CF/small \( r_h \) galaxies, at the 0.05 dex level. Based on the LZ relation derived for absolute magnitudes in different SDSS filters we conclude that the shift is partly in metallicity (∼0.05 dex) and partly in luminosity (up to 0.4 mag at \( M_B > -20 \)). We find tentative evidence that larger \( r_h \) galaxies (which tend to be observed with small CFs) may have enhanced metallicity for a given mass/luminosity in pairs relative to the field. We investigate what fundamental parameters may drive the empirical dependence of the LZ/MZ offsets on \( r_h \). We conclude that a dependence on bulge fraction provides a consistent picture with the observations. In this scenario, the smaller galaxies (with half light radii typically \( r_h < 3 h_70^{-1} \) kpc) tend to have larger bulges which delay the interaction-induced star formation.

4. AGN fraction. For given cuts in color, bulge fraction, and smoothness, pairs of galaxies have AGN fractions consistent with the field, consistent with the conclusions of Barton et al. (2000) and Alonso et al. (2007). However, redder galaxies and those with more symmetric morphologies have higher AGN fractions (∼20–30%) than blue or asymmetric galaxies (∼5–10%).

Overall, our results support the picture that close interactions (within a few tens of kpc) between galaxies cause gas to inflow to the central regions, engaging new star formation. The outer parts of the galaxy and the disk are largely unaffected by additional star formation (e.g., Paper II). The process of gas infall and star formation is most efficient for approximately equal mass...
The SDSS Web site is http://www.sdss.org/. The SDSS is a joint project of the University of Chicago, Fermilab, Institute for Advanced Study, the Japanese Participation Group, Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Scientist Group, Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, Ohio State University, University of Pittsburgh, University of Portsmouth, Princeton University, the United States Naval Observatory, and the University of Washington.

REFERENCES

Alonso, M. S., Lambas, D. G., Tissera, P. B., & Coldwell, G. 2006, MNRAS, 367, 1029
Alonso, M. S., Lambas, D. G., Tissera, P. B., & Coldwell, G. 2007, MNRAS, 375, 1017
Alonso, M. S., Tissera, P. B., Coldwell, G., & Lambas, D. G. 2004, MNRAS, 352, 1081
Balogh, M., Morris, S., Yee, H. K. C., Carlberg, R. G., & Ellingson, E. 1999, ApJ, 527, 54
Balogh, M., Schade, D., Morris, S., Yee, H. K. C., Carlberg, R. G., & Ellingson, E. 1998, ApJ, 504, 75
Barnes, J. E., & Hernquist, L. 1992, ARA&A, 30, 705
Barnes, J. E., & Hernquist, L. 1996, ApJ, 471, 115
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., Bromley, B. C., van Zee, L., & Kenyon, S. J. 2001, AJ, 121, 625
Barton, E. J., Geller, M. J., & Kenyon, S. J. 2000, ApJ, 530, 660
Bekki, K., & Noguchi, M. 1994, A&A, 290, 7
Bekki, K., Shioya, Y., & Whiting, M. 2006, MNRAS, 371, 805
Blanton, M. R., & BRiL, A. A. 2007, ApJ, 664, 791
Bresolin, F. 2007, ApJ, 656, 186
Bresolin, F., Garnett, D. R., & Kennicutt, R. C. 2004, ApJ, 615, 228
Brinchmann, J., Charlton, S., White, S. D. M., Tremonti, C., Kauffmann, G., Heckman, T., & Brinkmann, J. 2004, MNRAS, 351, 1151
Brinchmann, J., & Ellis, R. S. 2000, ApJ, 536, L77
Brooks, A. M., Governato, F., Booth, C. M., Willman, B., Gardner, J. P., Wadsley, J., Stinson, G., & Quinn, T. 2007, ApJ, 655, L17
Bruzual, A. G., & Charlot, S. 1993, ApJ, 405, 538
Bushouse, H. A. 1987, ApJ, 320, 49
Byrd, G., & Valtonen, M. 1990, ApJ, 350, 89
Carlberg, R. G., Pritchet, C. J., & Infante, L. 1994, ApJ, 435, 540
Cox, T. J., Jonsson, P., Somerville, R. S., Primack, J. R., & Dekel, A. 2008, MNRAS, 384, 386
de la Rosa, I. G., de Carvalho, R. R., Vazdekis, A., & Barbuy, B. 2007, AJ, 133, 330
Denicolo, G., Terlevich, R., & Terlevich, E. 2002, MNRAS, 330, 69
D’Erofferio, A., Kauffmann, G., Balogh, M. L., White, S. D. M., Schade, D., & Ellingson, E. 2001, MNRAS, 323, 999
Di Matteo, T., Springel, V., & Hernquist, L. 2005, Nature, 433, 604
Dressler, A. 1980, ApJ, 236, 351
Drory, N., Bender, R., & Hopp, U. 2004, ApJ, 616, L103
Ellison, S. L., & Kewley, L. J. 2005, in Proc. The Fabulous Destiny of Galaxies; Bridging the Past and Present, ed. V. Le, A. Brun, S. Maurice Arnouts, & D. Burgarella, p 53
Ellison, S. L., Patton, D. R., Simard, L., & McConnell, A. W. 2008, ApJ, 672, L107
Ferrarese, L., & Ford, H. 2005, Space Sci. Rev., 116, 523
Finlator, K., & Davé, R. 2008, MNRAS, in press (arXiv:0704.3100)
Friedli, D., & Benz, W. 1993, A&A, 268, 67
Geller, M. J., Kenyon, S. J., Barton, E. J., Jarrett, T., & Kewley, L. J. 2006, AJ, 132, 2243
Gerin, M., Combes, F., & Athanassoula, E. 1990, A&A, 230, 37
Gomez, P., et al. 2003, ApJ, 584, 210
Hoopes, C. G., et al. 2007, ApJS, 173, 441
Hummel, E. 1981, A&A, 96, 111
Kauffmann, G., et al. 2003b, MNRAS, 341, 33
Kobulnicky, H. A., & Kennicutt, R. C., Jr., & Pizagno, J. L. 1999, ApJ, 514, 544
Kobulnicky, H. A., & Kewley, L. J. 2004, ApJ, 617, 240
Koppen, J., Weidner, C., & Kroupa, P. 2007, MNRAS, 375, 673
Lambas, D. G., Tissera, P. B., Alonso, M. S., & Coldwell, G. 2003, MNRAS, 346, 1189

Figure 17. AGN fraction for all control galaxies (filled black rectangles) and close pairs (gray shaded rectangles) as a function of redshift. The width of each rectangle shows the size of the redshift bin, and the height indicates the median AGN fraction in that bin and its spread based on Poisson statistics.
Larson, R. B., & Tinsley, B. M. 1978, ApJ, 219, 46
Lee, H., Skillman, E. D., Cannon, J. M., Jackson, D. C., Gehrz, R. D., Polomski, E. F., & Woodward, C. E. 2006, ApJ, 647, 970
Lewis, I., et al. 2002, MNRAS, 334, 673
Li, C., Kauffmann, G., Heckman, T. M., Jing, Y. P., & White, S. D. M. 2008a, MNRAS, in press (arXiv:0712.3792)
Li, C., Kauffmann, G., Heckman, T. M., White, S. D. M., & Jing, Y. P. 2008b, MNRAS, in press (arXiv:0712.0383)
Li, C., Kauffmann, G., Wang, L., White, S. D. M., Heckman, T. M., & Jing, Y. P. 2006, MNRAS, 373, 457
Maier, C., Lilly, S. J., Carollo, C. M., Stockton, A., & Brodwin, M. 2005, ApJ, 634, 849
Marconi, A., Risaliti, G., Gilli, R., Hunt, L. K., Maiolino, R., & Salvati, M. 2004, MNRAS, 351, 169
Martin, P., & Roy, J.-R. 1994, ApJ, 424, 599
Masjedi, M., et al. 2006, ApJ, 644, 54
Mastropietro, C., Moore, B., Mayer, L., Wadsley, J., & Stadel, J. 2005, MNRAS, 363, 509
McGaugh, S. S. 1991, ApJ, 380, 140
McIntosh, D. H., Rix, H.-W., & Caldwell, N. 2004, ApJ, 610, 161
Mendes de Oliveira, C., Coelho, P., González, J. J., & Barbuy, B. 2005, AJ, 130, 55
Mihos, C., & Hernquist, L. 1994, ApJ, 425, L13
Mihos, C., & Hernquist, L. 1996, ApJ, 464, 641
Miller, C. J., Nichol, R. C., Gomez, P. L., Hopkins, A. M., & Bernardi, M. 2003, ApJ, 597, 142
Moore, B., Lake, G., Quinn, T., & Stadel, J. 1999, MNRAS, 304, 465
Mohtие, M., Baldry, I. K., & Bamford, S. P. 2007, MNRAS, 382, 801
Nikolic, B., Cullen, H., & Alexander, P. 2004, MNRAS, 355, 874
Pagel, B. E. J., Edmunds, M. G., Blackwell, D. E., Chun, M. S., & Smith, G. 1979, MNRAS, 189, 95
Patton, D. R., & Atfield, J. E. 2008, ApJ, submitted
Patton, D. R., Carlberg, R. G., Marzke, R. O., Pritchet, C. J., da-Costa, L. N., & Pellegrini, P. S. 2000, ApJ, 536, 153
Patton, D. R., Grant, J. K., Simard, L., Pritchet, C. J., Carlberg, R. G., & Borne, K. D. 2005, AJ, 130, 2043
Patton, D. R., Pritchet, C. J., Yee, H. K. C., Ellingson, E., & Carlberg, R. G. 1997, ApJ, 475, 29
Perez, M. J., Tissera, P. B., Lambas, D. G., & Scannapieco, C. 2006a, A&A, 449, 23
Perez, M. J., Tissera, P. B., Scannapieco, C., Lambas, D. G., & de Rossi, M. E. 2006b, A&A, 459, 361
Pettini, M., & Pagel, B. E. J. 2004, MNRAS, 348, L59
Pimbblet, K., Smail, I., Kodama, T., Couch, W., Edge, A., Zabludoff, A., & O’Hely, E. 2002, MNRAS, 331, 333
Poggianti, B., Smail, I., Dressler, A., Couch, W., Barger, A., Butcher, H., Ellis, R., & Oemler, A. 1999, ApJ, 518, 576
Proctor, R. N., Forbes, D. A., Hau, G. K. T., Beasley, M. A., de Silva, G. M., Contreras, R., & Terlevich, A. I. 2004, MNRAS, 349, 1381
Rupke, D. S. N., Veilleux, S., & Baker, A. J. 2008, ApJ, 674, 172
Salzer, J. I., Lee, J. C., Melbourne, J., Hinz, J. L., Alonso-Herrero, A., & Jugren, A. 2005, ApJ, 624, 661
Schmitt, H. R. 2001, AJ, 122, 2243
Shankar, F., Salucci, P., Granato, G. L., De Zotti, G., & Danese, L. 2004, MNRAS, 354, 1020
Shioya, Y., Bekki, K., & Couch, W. J. 2004, ApJ, 601, 654
Simard, L., et al. 2002, ApJS, 142, 1
Smith, B. J., Struck, C., Hancock, M., Appleton, P. N., Charmandaris, V., & Reach, W. T. 2007, AJ, 133, 791
Sorrentino, G., Radovich, M., & Rifatto, A. 2006, A&A, 451, 809
Stauffer, J. R. 1992, ApJ, 262, 66
Storchi-Bergmann, T., Gonzalez-Delgado, R. M., Schmitt, H. R., Cid-Fernandes, R., & Heckman, T. 2001, ApJ, 559, 147
Strauss, M. A., et al. 2002, AJ, 124, 1810
Tremonti, C., et al. 2004, ApJ, 693, 898
Wake, D. A., Collins, C. A., Nichol, R. C., Jones, L. R., & Burke, D. J. 2005, ApJ, 627, 186
Whitmore, B. C., Gilmore, D. M., & Jones, C. 1993, ApJ, 407, 489
Woods, D. F., & Geller, M. J. 2007, AJ, 134, 527
Woods, D. F., Geller, M. J., & Barton, E. J. 2006, AJ, 132, 197
Xu, C., & Sulentic, J. W. 1991, ApJ, 374, 407
Zaritsky, D., Kennicutt, R. C., Jr., & Huchra, J. P. 1994, ApJ, 420, 87
Zheng, Z. X., et al. 2007, ApJ, 661, L47