Galaxy pairs in the Sloan Digital Sky Survey - VIII: The observational properties of post-merger galaxies.

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ABSTRACT

In order to investigate the effects of galaxy mergers throughout the interaction sequence, we present a study of 10,800 galaxies in close pairs and a smaller sample of 97 post-mergers identified in the Sloan Digital Sky Survey. We find that the average central star formation rate (SFR) enhancement ($\times 3.5$) and the fraction of starbursts (20 per cent) peak in the post-merger sample. The post-mergers also show a stronger deficit in gas phase metallicity than the closest pairs, being more metal-poor than their control by -0.09 dex. Combined with the observed trends in SFR and the timescales predicted in merger simulations, we estimate that the post-mergers in our sample have undergone coalescence within the last few hundred Myr. In contrast with the incidence of star-forming galaxies, the frequency of active galactic nuclei (AGN) peaks in the post-mergers, outnumbering AGN in the control sample by a factor of 3.75. Moreover, amongst the galaxies that host an AGN, the black hole accretion rates in the closest pairs and post-mergers are higher by a factor of ~ 3 than AGN in the control sample. These results are consistent with a picture in which star formation is initiated early on in the encounter, with AGN activity peaking post-coalescence.

Key words: Galaxies: interactions, galaxies: abundances, galaxies: active, galaxies: evolution, galaxies: Seyfert, galaxies: starburst

1 INTRODUCTION

Galaxy mergers represent a cornerstone in our picture of hierarchical galaxy evolution. In addition to building up the stellar mass in galaxies, mergers are predicted to trigger central starbursts, feed the central supermassive black hole and potentially completely transform the galaxy's morphology (e.g. Barnes & Hernquist 1996; Di Matteo, Springel & Hernquist 2005; Springel, Di Matteo & Hernquist 2005; Di Matteo et al. 2007, 2008; Cox et al. 2008; Montuori et al. 2010; Rupke, Kewley & Barnes 2010; Perez et al. 2011; Torrey et al. 2012). There has been considerable observational work over the last decades to confirm these theoretical predictions, which bear out many of the general, qualitative predictions of the simulations over a range of redshifts (e.g. Kennicutt et al. 1987; Barton, Geller & Kenyon 2000; Kewley, Geller & Barton 2006; Woods, Geller & Barton 2006; Smith et al. 2007; Jogee et al. 2009; Rupke, Kewley & Chien 2010; Koss et al. 2010, 2012; Silverman et al. 2011; Wong et al. 2011; Ramos-Almeida et al. 2011, 2012; Xu et al. 2012; Cotini et al. 2013; Lanz et al. 2013). However, a full and detailed picture of the merger transformation requires large samples of galaxies that span a range in mass, mass ratio, structural properties, environments and projected separation, since all of these properties are likely to impact the specific outcome of a merger.

Moreover, a combination of both spectroscopic and imaging data, which yields simultaneous information on morphology, metallicity, star formation and black hole accretion rates etc. is needed to fully characterize the changes that these galaxies undergo. Finally, a carefully matched control sample is essential in order to disentangle the effects of mergers from trends that are intrinsically present in the galaxy population (Perez et al. 2009).

The Sloan Digital Sky Survey (SDSS) is well suited to this task, providing public imaging and spectroscopic data for approximately one million galaxies in the nearby universe. By combining the imaging and spectroscopic samples, it has been possible to tackle many aspects of galaxy mergers with unparalleled statistics. Samples of either close spectroscopic pairs, or morphologically classified mergers have been used to investigate the impact of galaxy interactions on colours (Ellison et al. 2010; Patton et al. 2011; Alonso et al. 2012; Lambas et al. 2012), star formation rates (Nikolic, Cullen & Alexander 2004; Alonso et al. 2006; Ellison et al. 2008, 2013; Li et al 2008a; Scudder et al. 2012b; Patton et al. 2013), metallicity (Michel-Dansac et al. 2008; Ellison et al. 2008; Reichard et al. 2009; Peeples et al. 2009; Alonso, Michel-Dansac & Lambas 2010; Scudder et al. 2012b; Chung et al. 2013), morphology (Ellison et al. 2010; Darg et al. 2010; Casteels et al. 2013), gas consumption (Fertig et al. in preparation; Scudder et al. in prepa-

ration), infra-red emission (Hwang et al. 2010, 2011; Ellison et al. 2013) and nuclear activity (Alonso et al. 2007; Woods & Geller 2007; Li et al. 2008b; Ellison et al. 2008, 2011; Rogers et al. 2009; Darg et al. 2010; Liu, Shen & Strauss 2012; Sabater et al. 2013).

Although the observational signatures of mergers are now well documented, quantifying the relevent timescales for star formation and black hole accretion is more challenging to pin down. Early simulations (e.g. Mihos & Hernquist 1994, 1996) found that the duration of merger-triggered starbursts was fairly short, on the order of tens of megayears. At the time, similarly short timescales had also been inferred from observations of mergers (e.g. Larson & Tinsley 1978; Kennicutt et al. 1987). The natural projected separations on which to study the effects of mergers would therefore be at most a few tens of kpc. In more recent works, the observationally informed duration of triggered star formation has been extended to several hundred megayears (e.g. Barton, Geller & Kenyon 2000; Knapen & James 2009; Woods et al. 2010). For relative velocities on the order of a few hundred km s^{-1}, this corresponds to projected separations up to $\sim 50 \ h_{70}^{-1}$ kpc. Indeed, this has been the typical separation that most studies of close pairs have selected, with enhanced star formation rates (SFRs) usually detected within projected separations $\sim 30 \ h_{70}^{-1}$ kpc (e.g. Barton et al. 2000; Alonso et al. 2007; Domingue et al. 2009; Wong et al. 2011). However, it has recently been shown that the effects of galaxy interactions can be detected in pairs with separations in excess of $50 \ h_{70}^{-1}$ kpc (e.g. Park & Choi 2009; Scudder et al. 2012b; Patton et al. 2011). Using a new methodology for identifying pairs and control samples out to projected separations of 1 Mpc, Patton et al. (2013) have recently shown that the SFRs in SDSS galaxy pairs only decline to the level of a control sample at separations beyond $150 \ h_{70}^{-1}$ kpc. Perhaps even more surprisingly, Patton et al. (2013) also determined that the integrated star formation rate enhancement in galaxy interactions is actually *dominated* by widely separated pairs, ($50 < r_p < 150$ h_{70}^{-1} kpc) which are often excluded from merger studies. These results appear to be robust, and not simply a feature of the analysis technique, as has recently been shown to apply to correlation function analyses (Robaina & Bell 2012). Moreover, the detection of enhanced SFRs at wide separations is consistent with the much longer timescales (up to a Gyr or more) for interaction-induced star formation predicted by contemporary hydrodynamical simulations (e.g. Cox et al 2006, 2008; Torrey et al 2012). The short timescales inferred from early observational studies (e.g. Larson & Tinsley 1978) may be in part a selection bias whereby the morphological disturbances (as a sign of interaction) favour short post-pericentre timescales, whereas samples of pairs more fully sample the full interaction sequence (Lotz et al. 2008).

With the recent extension of merger samples out to projected separations of 1 Mpc, and with the interpretive framework provided by modern simulations, we are now converging on a fairly complete view of galaxy-galaxy interactions. However, there is one piece of the merger story that is still missing from studies of galaxy pairs: final coalescence and post-merger evolution. Merger simulations (e.g. Mihos & Hernquist 1996; Di Matteo et al 2005; Springel et al. 2005; Cox et al. 2006; Di Matteo et al. 2007; Johansson, Naab & Burkert 2009; Montuori et al. 2010; Debuhr, Quataert & Ma 2011; Torrey et al. 2012) indicate that the most intense bursts of star formation (and black hole accretion) happen around the time of coalescence, so it is important to include this component in observational studies. Certain selection criteria are known to frequently identify late stage mergers, most notably the luminous and ultraluminous infra-red galaxies (LIRGs and ULIRGs, e.g. Kartaltepe et al. 2010 and references therein). However, selection based on a fixed IR luminosity is likely to be biased towards the most massive, most highly star-forming mergers (e.g. Hwang et al. 2010; Ellison et al. 2013). Very few systematic studies of the post-merger phase exist. Carpineti et al. (2012) identify a sample of 30 spheroidal post-mergers from which they measure an enhanced fraction of active galactic nuclei (AGN). However, without a well matched and homogeneously analysed sample of galaxies in the pre-merger phase, it is not straightforward to quantify the impact of final coalescence relative to earlier stages in the interaction sequence.

The goal of this paper is to identify a sample of post-merger galaxies in the SDSS and analyse them identically to the sample of close pairs studied in our previous works. In this way, it is possible to follow the evolution of the merger to its final stages. One of the strengths of this work is that we can apply identical analysis techniques to the pre- and post-merger phases, ensuring that the data are comparable in the two regimes. In Section 2 we describe the various samples used in this work: close pairs, post-mergers and their respective controls. Sections 3, 4 and 5 deal with changes in the star-forming, metallicity and nuclear properties, respectively.

We adopt a cosmology of $\Omega_\Lambda = 0.7$, $\Omega_M = 0.3$, $H_0 = 70$ km/s/Mpc.

2 SAMPLE SELECTION

2.1 Close pairs

The starting point for the selection of our sample of galaxy pairs is the SDSS DR7 Main Galaxy Sample ($14.0 \leqslant m_r \leqslant 17.77$) with a redshift range $0.01 \leqslant z \leqslant 0.2$ and SDSS specclass=2. The criteria and justification for our selection of pairs from the SDSS has been discussed extensively in our previous papers on this topic (e.g. Patton et al. 2011; Scudder et al. 2012b; Ellison et al. 2011, 2013). We therefore review only briefly the main requirements and refer the interested reader to these earlier works for more complete details and discussions on selection biases etc. In order to be included in our sample of close pairs, we require that a galaxy has a companion that fulfills the following criteria:

(i) A projected physical separation $r_p \leqslant 80 \ h_{70}^{-1}$ kpc.
(ii) A line of sight velocity difference $\Delta V \leqslant 300$ km s^{-1}, in order to minimize chance projections.
(iii) A stellar mass ratio of $0.25 \leqslant M_1/M_2 \leqslant 4$.

There are two main differences in the pairs sample used in this paper compared to our previous works. The first is our choice of mass ratios; in our previous papers, we have investigated the effect of mergers on pairs with stellar masses that differ by up to a factor of 10. However, the goal of the current study is to investigate the evolution of mergers as they progress through the coalescence phase. It is therefore desirable to identify close pairs that are, as far as is possible, pre-merger analogs to the post-mergers in our sample. The visual or automated selection of post-mergers, both of which rely on galaxy asymmetry, is likely to be highly skewed towards major mergers, with approximately equal stellar masses (e.g. Lotz et al. 2010). We have therefore restricted our sample to pairs whose mass ratios are within a factor of 4 of one another. However, it is worth noting that our results change very little with this more restrictive mass ratio cut, as may have been expected based on our previous work (e.g. Ellison et al. 2011; Scudder et al. 2012b). This invariance also means that our exact choice of mass ratio criterion does not alter any of our results.

The second main difference in the work presented here compared with our previous pairs' studies, is that we adopt total stel-

Figure 2. Examples of galaxies originally classified as post-mergers in the sample of Darg et al. (2010), but rejected during our visual classifications. The first 3 have a resolved companion, the last 2 are classified as 'normal' irregular galaxies. The SDSS object ID is given in the top of each panel.

Figure 1. Comparison between the Mendel et al. (2013a) and Kauffmann et al. (2003a) stellar masses (denoted as M13 and K03, respectively, in the figure) for our sample of close pairs, as a function of projected separation.

lar masses determined from the Sersic fits presented by Mendel et al. (2013a), rather than those derived by Kauffmann et al. (2003a). The Mendel et al. (2013a) masses use the updated SDSS photometry provided by Simard et al. (2011), which has been demonstrated to be robust even in the presence of a very close companion. As shown by Mendel et al. (2013a), the two sets of masses are generally in good agreement, although the masses of Kauffmann et al. (2003a) are, $\sim 0.05 - 0.1$ dex lighter than those derived by Mendel et al. (2013a), depending on the mass. In Figure 1 we compare the Mendel (2013a) and Kauffmann et al. (2003a) masses as a function of projected separation. In addition to the slight offset to higher masses in the Mendel et al. (2013a) catalog, it can be seen that not only is the scatter between the two values larger at the smallest separations, but there is a an overall increase in the trend towards lighter masses in the Kauffmann et al. (2003a) values at projected separations $r_p < 20 \ h_{70}^{-1}$ kpc. This is due to the use of improved photometry in crowded environments by Mendel et al. (2013a) for their mass determinations. For the post-mergers, we find that the masses from the two catalogs are in good agreement.

The SDSS is subject to significant spectroscopic incompleteness at angular separations $\theta < 55$ arcsec (Patton & Atfield 2008). If this incompleteness is not accounted for, a significant selection bias is introduced (e.g. Ellison et al. 2008). We therefore follow the strategy of our earlier works and apply a random culling[1] of 67.5% of pairs at separations $\theta > 55$ arcsec. There are 10,800 galaxies in the close pairs sample after the culling has been applied.

As described in the Introduction, our previous work has demonstrated that pairs remain significantly different from their control samples out to projected separations of $\sim 150 \ h_{70}^{-1}$ kpc (Patton et al. 2013). However, in the work presented here, we do not

include the full wide pairs sample, primarily because it requires a more complex control matching procedure that is not necessary for this work. We note that, as shown in Patton et al. (2013), SFR enhancements of the close pairs follow a gradual decline out to the wider separations; in this paper, we focus on extending the investigation of properties to the final stage of the merger sequence: coalescence.

2.2 Post-mergers

In order to identify galaxies in the final stages of their interaction, after the two individual galaxies have coalesced, we turn to the visual classifications of SDSS galaxies performed by the Galazy Zoo project. The basic Galazy Zoo sample selection includes $\sim 900,000$ galaxies from the SDSS DR6, as described by Lintott et al (2008). Darg et al. (2010) impose further requirements that the spectroscopic redshift of a galaxy must be $0.005 < z < 0.1$ and the extinction corrected r-band Petrosian magnitude be $m_r < 17.77$, from which they construct samples of galaxy mergers [2]. Based on an initial cut in the total merger vote fractions ($f_m > 0.4$), followed by further visual follow-up by a professional astronomer, Darg et al. (2010) have compiled two distinct Galazy Zoo merger catalogues. The first consists of binary mergers, akin to a morphologically selected version of our own spectroscopic close pairs sample. The second catalogue consists of post-mergers; single galaxies that are strongly disturbed, highly irregular, exhibit significant tidal features, or other signs of a recent interaction. The post-merger catalogue consists of 358 galaxies. By construction, the post-merger catalogue will only include those merger events that are sufficient to produce strong tidal features or otherwise visibly distort the galaxies in the SDSS images.

We have performed a further visual classification of galaxies in the post-merger catalogue in order to remove either a) galaxies that are irregular, but not apparently merging; these galaxies are consistent with morphologies of similar galaxies in the Hubble classification or b) late phase encounters (close pairs) that have not fully coalesced to a final post-merger state. Examples of these rejected categories are shown in Figure 2. We also require that, to be consistent with the selection of the close pairs, the post-merger galaxies have an SDSS specclass=2 and a Mendel et al. (2013a) mass available. The final sample of post-mergers consists of 97 galaxies, a selection of which is shown in Figure 3.

In Figure 4 we show the distribution of stellar masses, redshifts and local overdensity for both the post-merger and close pairs samples. Following our previous works, we compute local environmental densities, Σ_n:

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[1] An alternative strategy, which we have applied in Patton et al. (2013), is to apply a statistical weight that is a function of the projected separation. Since Patton et al. (2013) were particularly interested in wide separation pairs, assigning a higher weight to galaxies with small separations was preferable to simply excluding two-thirds of the sample at wide separations.

[2] In addition to the basic morphological classifications of 'spiral' and 'elliptical', Galaxy Zoo volunteers may also identify galaxies as 'mergers'.

Figure 3. A selection of 25 post-mergers from our sample of 97 that remain after our own visual classification of the Galaxy Zoo catalog. The SDSS object ID is given in the top of each panel.

Figure 4. The distribution of stellar masses (upper panel), redshifts (middle panel) and local overdensities (lower panel) for the close pairs (black solid line) and post-mergers (red dashed line).

$$\Sigma_n = \frac{n}{\pi d_n^2}, \qquad (1)$$

where d_n is the projected distance in Mpc to the nth nearest neighbour within ± 1000 km s^{-1}. Normalized densities, δ_n, are computed relative to the median Σ_n within a redshift slice ± 0.01. In this study we adopt $n = 5$.

Despite the difference in selection techniques, the stellar mass distributions of the pairs and post-mergers shown in Figure 4 are very similar. However, due to the imposed redshift cut of the Galaxy Zoo selection, the post-mergers sample is truncated at significantly lower redshifts than the close pairs. This is not *a priori* a problem, since we will describe in the next section how a control sample is matched in redshift. The difference in redshift ranges will only impact our results if there is an underlying dependence of merger-induced effects on redshift. We have therefore repeated all of the analysis presented in this paper and can confirm that the results are robust to a redshift cut in the pairs at $z = 0.1$. However, since such a redshift cut excludes approximately one-third of the pairs sample, we have not imposed a z criterion on the pairs, in order to maximise the statistical sample size. Similarly, the distribution of local overdensities differs between the pairs and post-mergers; this is again tackled by including environment as one of the parameters in our control sample matching. Therefore, the differential changes in, for example, star formation rate, can be compared, even when the underlying distributions of mass, environment etc. may differ.

2.3 Control samples

In previous works we have compiled control samples with a fixed number (typically ~ 10) of mass-, density- and redshift-matched galaxies with no close companion. However, in the current paper, we will be selecting subsets of galaxies from our main pairs sample (e.g. for studies of star forming or AGN properties), such that control samples are more conveniently created dynamically. The pool of possible control galaxies (for any subset of pairs) consists of all galaxies that have no spectroscopic companion within 80 h_{70}^{-1} kpc and with a relative velocity ΔV within 10,000 km s^{-1}. Due to the spectroscopic incompleteness of the SDSS, there will be many *bona fide* close pairs that are not in our pairs sample, and are therefore erroneously identified as potential control galaxies. In order to avoid using these unidentified pairs as controls, we utilize the Galaxy Zoo binary merger sample (Darg et al. 2010), since, unlike our close pairs sample, Galazy Zoo does not require the companion to have a spectroscopic redshift. We therefore additionally reject galaxies from the control pool if they have Galaxy Zoo merger vote fractions $f_m > 0$ (see Darg et al. 2010 and Ellison et al. 2013 for more details).

For a given pair or post-merger galaxy, all of the galaxies from the control pool within a redshift tolerance $\Delta z=0.005$, a mass tolerance $\Delta \log M_\star=0.1$ dex and a normalized local density tolerance $\Delta \delta_5=0.1$ dex are selected as controls. At least 5 matches are required, a limit which is achieved in > 90 per cent of cases (the typical number of matches is usually of the order several hundred).

If less than 5 matches are found, the tolerance is grown by a further Δz=0.005 in redshift, $\Delta \log M_\star$=0.1 dex in stellar mass and $\Delta \delta_5$=0.1 dex in normalized local density until the required number of matches is achieved.

2.4 Classification schemes and S/N requirements

From our complete sample of 10,800 galaxies in pairs and 97 post-mergers, various sub-samples are selected for the analysis presented in this paper. These criteria are primarily based on two parameters. First, the S/N in the 4 emission lines used in the AGN diagnostic diagram of Baldwin, Phillips & Terlevich (1981), namely [OIII] λ 5007, Hβ, Hα and [NII] λ 6584, hereafter collectively referred to as the BPT lines. Second, the choice of AGN or star-forming classification scheme that divides the BPT diagram. Ideally, one would adopt a uniform set of S/N and classification criteria to the whole sample. In practice, the different astrophysical tests we will carry out have varying requirements. The criteria we adopt in the analysis that follows are explained and justified in the relevent sections of the paper. However, it is useful to describe the basic motivations behind our choices in advance.

In Sections 3 and 5 we investigate the star-forming and AGN fractions in our sample. This experiment requires only a classification on the BPT diagram. To select galaxies that are *dominated* by star-formation we use the criteria of Kauffmann et al. (2003b)[3] and to select galaxies with *some* contribution from AGN we use the criteria of Stasinska et al. (2006). For the classification of galaxies as star-forming or AGN we require a S/N in all of the BPT lines of at least 5. Cid-Fernandes et al. (2010) have made a thorough investigation of the impact of S/N requirements on the selection of galaxies within the BPT diagram. They convincingly demonstrate that galaxies excluded (or included) by a given S/N criterion are not just a random sampling of galaxies with poorer quality spectra. For galaxies classified as AGN a low S/N more frequently selects galaxies with Low Ionization Nuclear Emission Region (LINER-like) spectra. We therefore require that the S/N of the BPT lines exceeds 5 for our calculation of AGN and (for consistency) star-forming fractions.

For the computation of gas phase metallicities, a similarly high S/N is required (e.g. Kewley & Ellison 2008), so we follow our previous work on the metallicity distribution in galaxy pairs and again adopt S/N>5 (Scudder et al. 2012b). However, since the SFRs themselves are mostly driven by the strength of the Hα line, which is typically the strongest of the BPT lines by a large margin, we are able to reduce the collective S/N requirement of the BPT lines to be S/N>1 when quantifying SFRs. This is similar to the criterion we have recently adopted in our study of SFRs in wide pairs (Patton et al. 2013).

Following our previous work, we will trace the impact of the galaxy interaction relative to the control sample by calculating the offset (Δ), measured on a logarithmic scale, between a given galaxy metric (such as SFR, which is described more fully in Section 3.2) and the median value of its control galaxy values. For example,

$$\Delta \text{SFR} = \log \text{SFR}_{\text{pair}} - \log \text{SFR}_{\text{control}} \qquad (2)$$

such than an offset of Δ SFR = 1.0 indicates a SFR enhance-

Figure 5. The fraction of galaxies classified as star-forming as a function of projected separation. In the upper panel, filled points represent pairs and (in the grey shaded box) post mergers and open triangles show the star-forming fraction in the control sample. Since each galaxy has its own set of controls matched in redshift, mass and environment, the controls can also be plotted as a function of r_p to test for any underlying dependences. In the lower panel we show the ratio of the star-forming fraction in the pairs and post-mergers relative to their controls.

ment of a factor of 10 above what would be expected for an isolated galaxy of this mass, environment and redshift.

3 TRIGGERED STAR FORMATION

3.1 The fraction of star-forming galaxies

We begin our investigation of the properties of post-mergers by considering the fraction of galaxies that are dominated by star-formation. Star-forming galaxies are selected using the criteria of Kauffmann et al. (2003b) and requiring a S/N > 5 in the BPT lines. The top panel of Figure 5 shows the fraction of galaxies classified as star-forming in both the sample of close pairs and the post-merger sample. The open triangles in the upper panel indicate the fraction of star-forming galaxies in the control samples. Since each galaxy has its own set of matched controls, we are able to show the controls as a function of r_p, so that the control sample will mirror any changes in the underlying galaxy population. For example, it can be seen that the controls that are matched to the post-merger sample have a significantly higher star-forming fraction than the controls matched to the pairs. This is mainly driven by the typically lower density environments of the post-merger sample selected by

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[3] According to Stasinska et al. (2006) star-forming galaxies selected by the Kauffmann et al. (2003b) criteria may have up to 3 per cent contribution from AGN.

Galazy Zoo compared with our spectroscopic pairs selected. The top panel of Figure 5 therefore demonstrates the importance of control matching. However, for most subsequent metrics of merger-induced effects studied in this paper we will show only the values relative to the controls, akin to the lower panel of Figure 5.

The lower panel of Figure 5 shows the *excess* star-forming fraction, i.e. the ratio of the star-forming fractions in the mergers relative to their controls. It can be seen that the pairs exhibit an enhancement in the star-forming fraction out to at least $80\ h_{70}^{-1}$ kpc, which is the limit of our sample. This is complementary to the results of Scudder et al. (2012b) and Patton et al. (2013), who have recently shown that star formation *rates* remain elevated out to similar separations (dropping to the control value by $r_p \sim 150\ h_{70}^{-1}$ kpc). However, the increase in the star-forming fraction from $r_p \sim 80\ h_{70}^{-1}$ kpc to $r_p \sim 10\ h_{70}^{-1}$ kpc is rather modest, increasing from a factor of ~ 2 to 3 above the control sample over this separation range. Similarly, although the raw fraction of star-forming galaxies in the post-merger sample is higher than in the close pairs (upper panel of Figure 5), so is the fraction of star-forming galaxies in the matched control sample. Therefore, the excess of star-forming galaxies in the post-mergers is actually consistent with the value in the closest pairs. This result indicates that galaxies tend to become classified as star-forming well before final coalescence.

3.2   Star formation rate enhancements

We next consider the *rates* of star formation within those galaxies classified as star-forming. The strength of the Hα line relative to the other BPT lines allows us to relax the collective BPT line S/N constraint to 1, without loss of accuracy in the determination of the star formation rate (the qualitative trends in our results are not sensitive to this choice of S/N cut). The SFRs are taken from Brinchmann et al. (2004) and are based on template fits to the SDSS spectra, yielding 'fibre' SFRs that are applicable to the region of the galaxy covered by the 3 arcsecond SDSS aperture. Brinchmann et al. (2004) also apply a colour-dependent correction for the light outside of the fibre, in order to determine 'total' SFRs. In this paper, we additionally infer the SFR outside of the 3 arcsec fibre by subtracting the fibre SFR from the total value.

In Figure 6 we show the enhancement in the SFR (Δ SFR) in both the close pair and post-merger samples relative to their respective matched control samples. Both fibre (filled points) and outer SFRs (open points) show an excess in the close pairs relative to their controls out to at least $80\ h_{70}^{-1}$ kpc. Although previous works have inferred that the bulk of triggered star formation is centrally concentrated (Barton et al. 2003; Bergvall et al. 2003; Ellison et al. 2010; Patton et al. 2011; Schmidt et al. 2013), Figure 6 shows explicitly that a small amount of star formation is also triggered in a more spatially extended component. Star formation on an extended spatial scale has also been predicted in simulations (e.g. Powell et al. 2013). The pre-coalescence SFRs in our sample of pairs are, on average, a factor of ~ 2 higher than their control in the fibres and 25 per cent higher in the outer parts (beyond a few kpc). The post-mergers show further enhancements in their SFRs in both the outer and fibre measurements; on average the post-mergers have SFRs that are higher by 70 per cent (outer) and a factor of 3.5 (fibre) than their control samples. These enhancements exceed (in both cases) the pre-merger values by about 40 per cent. Therefore, whereas the pre-coalescence phase of the interaction most strongly affects central star formation, the final merger increases the SFR more uniformly on a broader spatial scale.

Figure 6. The enhancement in SFR for close pairs of galaxies that are classified as star-forming. Filled points show the enhancements in the fibre, hollow points show the SFR enhancements outside of the fibre. The points in the grey shaded box show the enhancements for galaxies in the SDSS post-merger sample presented here.

3.3   The frequency of starbursts

Whilst Figure 6 measures the evolution of the average Δ SFR, it does not tell us about the distribution of SFR enhancements, including how frequently real starburst galaxies are formed in the merger process. Whilst the *average* SFR enhancement in post-mergers may be only a factor of 3.5, this may be due to a mix of galaxies that are already quenched and some that are forming stars very aggressively. For example, Di Matteo et al. (2007, 2008) show that galaxies that experience more modest tidal interactions during their first pericentric passage are able to preserve a higher gas reservoir for a more intense burst of star formation at coalescence.

In Scudder et al. (2012b) we investigated the cumulative distributions of Δ SFR in close pairs as a function of both mass ratio and separations. It was shown that whilst close pairs of all mass ratios and separations may exhibit modest SFR enhancements (up to a factor of 2), enhancements exceeding a factor of 10 were restricted to approximately equal mass mergers with small projected separations (although starbursts are rare, even within these criteria). In this paper, we take a slightly different approach, and plot the fraction of star-forming galaxies with enhancements greater than some threshold. Again, we require that the BPT lines all have a S/N > 1 and the galaxies are classified as star-forming according to the Kauffmann et al. (2003b) criteria. We set the SFR enhancement thresholds to be a factor of 2, 5 and 10 above the matched control sample (i.e. Δ SFR > 0.3, 0.7, 1.0).

Figure 7 shows that the fraction of galaxies exceeding each of these fibre SFR thesholds increases towards the smallest separations and peaks in the post-merger sample. Enhancements of a factor of two are common; 60 – 70 per cent of the closest pairs and post-mergers exhibit an increase at this level. In the post-mergers, 40 per cent of galaxies have SFR enhancements of at least a factor of five. True starbursts are relatively rare, rising from ~ 5 per cent in the widest separation pairs to ~ 15 per cent in the closest pairs and 20 per cent in the post-mergers. These starburst fractions are in

of stellar mass produced) may be equivalent to a long, gentle period of production. A complementary demonstration of the recent star formation history, that probes a more extended timescale, comes from a measurement of the fraction of stellar mass in a 'young' component. Recently, Mendel et al. (2013b) have used a spectral decomposition technique to investigate the properties of quenched galaxies in the SDSS. The technique adopts two spectral templates (Bruzual & Charlot 2003), one consisting of a 7 Gyr old single stellar population with solar metallicity, and the other of a 300 Myr old starburst. The spectral decomposition determines the fractional contribution to the stellar mass from the young stellar template, f_{young}.

Figure 8 shows the median difference between f_{young} measured in the sample of pairs and post-mergers, compared to f_{young} measured in the matched control samples. Since f_{young} is not a commonly used quantity in the literature, in the top panel of Figure 8 we show the absolute values of this quantity for reference. We include all of the galaxies for which a spectral decomposition is successful and are classified as star-forming (Kauffmann et al. 2003b). The enhancement in f_{young} can be used to deduce the increase in the stellar mass due to star formation over $\sim 300 - 500$ Myr timescales. This is much shorter than the full interaction timescale probed by the close pairs, so changes in f_{young} in pairs does not provide a complete inventory of new stellar mass in the pre-merger phase. However, as we argue below, the time since coalescence of our post-merger sample is likely to be sufficiently short that Δf_{young} for this population will encapsulate the integrated stellar mass formed during this final stage. Figure 8 shows a median enhancement of f_{young} in post-mergers that corresponds to an approximate doubling of the fraction of mass in young stars, relative to a matched control sample. Therefore, by using f_{young} as a complementary measure of recent (but not instantaneous) star formation, we can see that coalescence plays an important role in stellar mass production, despite the short timescale that these bursts are predicted to endure.

In summary of this section, we have found that star formation is triggered early on in the interaction process. Whilst coalescence does induce further star formation, the SFRs are (on average) only modestly higher than during the pre-merger phase of the interaction. However, instantaneous SFRs do not provide the complete picture of star formation throughout the merger sequence. Indeed the combination of prolonged SFR enhancements out to wide separations (Patton et al. 2013) and the results presented here, indicate that typical post-pericentric bursts of star formation may endure for at least a Gyr, but that coalescence induced star formation may be more short-lived. Nonetheless, the short, intense burst of star formation that typifies coalescence can approximately double the fraction of mass in young stars.

4 CHANGES IN METALLICITY

Following Scudder et al. (2012a,b), we calculate the metallicity of star-forming galaxies according to the formalism of Kewley & Dopita (2002), as recently re-assessed by Kewley & Ellison (2008). In order to be consistent with our previous work, we require that galaxies are classified as star-forming according to the criteria of Kauffmann et al. (2003b) and have a S/N > 5 in Hα, Hβ, [OII] λ 3727, [OIII] $\lambda\lambda$ 4959, 5007 and [NII] λ 6584. In Figure 9 the change in metallicity, relative to the control sample, is plotted for both the close pairs and post-mergers. Figure 9 shows the now familiar trend in the pairs of a projected separation dependence that remains offset from the control sample out to at least 80 h_{70}^{-1} kpc.

Figure 7. The fraction of galaxies with fibre SFR enhancements at least a factor of 2, 5 or 10 (blue, cyan and purple points respectively) above their matched controls. The points in the grey shaded box show the enhancements for galaxies in the SDSS post-merger sample.

good agreement with the suite of simulations presented by Di Matteo et al. (2008), who find $13 - 22$ per cent of mergers show a SFR enhancement of at least a factor of 10, depending on the galaxy inclinations. The observational data therefore emphasize the conclusion made in the theoretical work of Di Matteo et al. (2008), that mergers do not always trigger starbursts.

3.4 The contribution of coalescence to stellar mass

Simulations of galaxy interactions generally conclude that intense bursts of star formation should occur at, or shortly before, coalescence (e.g. Di Matteo et al. 2007, 2008; Cox et al. 2008; Torrey et al. 2012). Although the results in Figures 6 and 7 qualitatively support these predictions, the SFRs at coalescence are predicted to frequently exceed the pre-merger phase by a factor of 10 or more. The increase in the average SFR and starburst frequency between the pre- and post-merger stages shown in Figures 6 and 7 are therefore quite modest. However, it is important to take into consideration the timing of the starburst which is usually both initiated, and reaches its peak, before the galaxies fully merge. These bursts tend to be intense, but short-lived, such that by a few hundred Myr after the coalescence the starburst has already largely subsided (e.g. Fig. 11 of Scudder et al. 2012b). It is therefore very unlikely, observationally, to catch a merger during the peak of star formation activity associated with the final merger. However, it is worth noting that since we do detect an enhancement in the SFR in post-mergers, coalescence has probably occured within this timescale of a few hundred Myrs, before 'quenching' becomes widespread, a conclusion supported by the metallicities discussed in Section 4.

So far in this section our analysis has focused on metrics associated with the current star formation activity in pairs and post-mergers. These metrics are derived from emission lines in HII regions that are ionized by the presence of young, hot stars. As argued above, a short 'snapshot' of the current SFR is unlikely catch a short, intense burst of star formation whose overall impact (in terms

Figure 9. The change in metallicity for close pairs of galaxies relative to their control sample. The point in the grey shaded box shows the metallicity offset for galaxies in the SDSS post-merger sample.

Figure 8. The fraction of galactic stellar mass contributed from young stars, f_{young}, as defined by Mendel et al. (2013b), for star-forming galaxies. The upper panel shows the absolute value of f_{young} in the mergers (filled circles) and control sample (open triangles). Since each galaxy has its own set of controls matched in redshift, mass and environment, the controls can also be plotted as a function of r_p to test for any underlying dependences. The lower panel shows the enhancement in median f_{young} for mergers relative to their control sample. The point in the grey shaded box shows the enhancement for galaxies in the SDSS post-merger sample.

The close pairs are typically 0.03 dex more metal-poor than the control sample, with the largest offset at the closest separations (Δ [O/H] ~ -0.07). The post-mergers are even more metal-poor, with a median Δ [O/H] ~ -0.09. Since metal-enrichment will follow a starburst, simulations predict that the metallicity dilution is most extreme within ~ 100 Myr of final coalescence, before it recovers to (or exceeds) its pre-merger value (e.g. Montuori et al. 2010; Scudder et al. 2012b; Torrey et al. 2012). The low observed metallicities in our post-merger sample support the conclusion drawn from the star formation rates, that coalescence is likely to have occurred in these galaxies relatively recently.

5   AGN IN POST-MERGERS

5.1   The fraction of AGN

In the same way that we calculated the fraction of galaxies classified as star-forming in Figure 5, we will now compute the fraction of galaxies that exhibit some contribution from AGN in their emission spectrum. The result of this calculation is particularly sensitive to the choice of BPT line S/N, as lowering the detection threshold

includes more LINER-like objects (e.g. Cid-Fernandes et al. 2010; Ellison et al. 2011). Due to the uncertain nature of LINERs (e.g. Stasinska et al. 2008; Cid Fernandes et al. 2011; Yan & Blanton 2012), it is preferable to restrict ourselves to Seyfert-like spectra and we therefore impose a S/N > 5 requirement on the BPT lines for this basic classification. We adopt the Stasinska et al. (2006) classification in order to be consistent with our previous work (Ellison et al. 2011). However, we stress that the Stasinska et al. (2006) criteria select galaxies with a wide range of AGN contribution and include composite objects that also have significant star formation. Nonetheless, the Stasinska et al. (2006) selection is appropriate for determining the fraction of galaxies with measurable AGN contribution and it was shown by Ellison et al. (2011) that the basic trend of increasing AGN fraction with decreasing projected separation is not dependent on the choice of diagnostic.

In Figure 10 we plot the AGN excess, defined to be the fraction of galaxies with an AGN contribution in both the close pairs and post-merger samples, relative to the AGN fraction in their respective controls. The AGN excess is therefore a measure of how much more often a galaxy in a merger exhibits the signature of an AGN compared to a non-merger of the same stellar mass, redshift and environment. The qualitative picture for the close pairs is very similar to that presented in Ellison et al. (2011); a gradual rise in the frequency of AGN, which peaks at ~ 2.5 times the control value at the smallest separations. However, whereas in Ellison et al. (2011) we found an AGN excess only out to $r_p \sim 40\ h_{70}^{-1}$ kpc, in the present analysis we find a statistical excess out to at least $80\ h_{70}^{-1}$ kpc, where AGN are more common by 10–20 per cent than in the control sample. There are a few differences between our current work and that of Ellison et al. (2011) that may explain the AGN excess that is seen out to large separations. The first is the different range of mass ratios[4] used in this study (1:4) and Ellison et al. (2011, 1:10). Second, Ellison et al. (2011) had a much smaller control sample than

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[4] There is also a slightly different ΔV cut, 300 km s^{-1} used here, compared with 200 km s^{-1} in Ellison et al. (2011).

this work, only 10 control galaxies per pair, compared to several hundreds used here. However, having experimented with the two samples, neither of these aspects of the analysis seems to be the cause for the wide separation AGN excess seen in Figure 10. The main cause appears to be the control matching parameters. Ellison et al. (2011) matched only in mass and redshift, whereas this paper also matches in environment. Therefore, as shown in the mock surveys produced by Perez et al. (2009), whilst mass is arguably the most important parameter for matching within a control sample, environmental matching provides a small, but measurable, improvement in sensitivity.

The main contribution of this work is to add the post-merger galaxies to Figure 10. In contrast to the fraction of star-forming galaxies shown in Figure 5, there is a clear increase in the AGN fraction post-coalescence. The post-mergers have an AGN frequency that exceeds their matched control sample by a factor of 3.75. This confirms theoretical expectations that the accretion rate is increased the most during the final merger (Di Matteo et al. 2005; Springel et al. 2005; Johansson et al. 2009). A similar enhancement in AGN fraction was found in the spheroidal post-merger sample of Carpineti et al. (2012), but that work was not able to trace the increase in AGN occurence throughout the merger sequence. The high post-merger AGN fraction in our sample is also consistent with the observation that LIRGs and ULIRGs frequently exhibit nuclear activity (e.g. Yuan, Kewley & Sanders 2010; Petric et al. 2011; Ellison et al. 2013). One implication of the enhanced incidence of AGN shown in Figure 10 is that attempts to quantify the merger-induced AGN fraction from the identification of close pairs will likely underestimate the true value. Although AGN *may* be triggered during the early phase of an interaction (see also Rogers et al. 2009; Ellison et al. 2011; Silverman et al. 2011; Koss et al. 2012; Smith et al. 2012; Liu et al. 2012; Sabater et al. 2013), the AGN rate peaks post-coalescence. A similar conclusion has recently been reached by Canalizo & Stockton (2013) for a sample of low redshift ($z \sim 0.2$) quasars, which exhibit the signature of an intermediate-age starburst, in addition to the on-going AGN activity.

5.2 Black hole accretion rate

In order to quantify the black hole accretion rate in SDSS AGN, numerous studies have used the luminosity of the [OIII] emission line (e.g.Kauffmann et al. 2003b; Heckman et al. 2004; Chen et al. 2009; Liu et al. 2012). However, since star formation can also contribute to the [OIII] line flux, some studies have attempted to remove this possible contamination (e.g. Kauffmann & Heckman 2009; Wild, Heckman & Charlot 2010). In this paper, we have taken the approach of selecting galaxies which should have minimal (relative) contribution from star formation by selecting for this portion of the analysis galaxies that are classified as AGN by Kewley et al. (2001). These galaxies are above the 'maximum starburst' line computed from grids of models with varying metallicities and ionization parameters. Kauffmann & Heckman (2009) estimate that only $10 - 20$ per cent of the [OIII] flux should be contributed from star formation in AGN classified by Kewley et al. (2001). More recent tests by Wild et al. (2010) imply AGN contributions of close to unity, indicating that although the Kewley et al. (2001) was not necessarily designed as a 'pure AGN' line (e.g. see the discussion in Stasinska et al. 2006), it is effective at isolating galaxies with minimal contamination of the [OIII] line by star formation. However, the stringent nature of this AGN classification greatly reduces the size of the AGN sample and increases the statistical uncer-

Figure 10. The AGN excess, defined as the fraction of SDSS galaxies that are classified as an AGN according to the definition of Stasinska et al. (2006), relative to the fraction of AGN of their respective controls. The point in the grey shaded box shows the AGN excess for galaxies in the SDSS post-merger sample.

tainty of our results. Lowering the required S/N can partly offset this problem, but this comes at the expense of LINER contamination, as described in previous sections. The solution we adopt is to indeed lower the BPT S/N requirement to one, but also require detections of [OI] λ 6300 and [SII] λ 6717, 6731. We can then apply the LINER diagnostic of Kewley et al. (2006), allowing us to construct a sample of Seyfert-dominated spectra.

Figure 11 shows the enhancement in the [OIII] luminosity (Δ L[OIII]) for both the close pairs and post-merger galaxies. The statistics are noisier than for the other metrics investigated in this paper due to the small number of 'pure' Seyferts in our sample. Nonetheless, there is a clear enhancement in the [OIII] luminosity by a factor of $\sim 2 - 3$ for close pairs separated by less than 50 h_{70}^{-1} kpc, consistent with, for example, the recent work by Liu et al. (2012). The post-mergers show the largest accretion rate enhancement, albeit with a large error bar, as predicted by simulations of major mergers (e.g. Johansson et al. 2009).

6 DISCUSSION

Recently, Treister et al. (2012) found a correlation between the fraction of AGN associated with mergers and bolometric luminosity, claiming that mergers only trigger the most luminous AGN. It is therefore of note that despite the enhancement in the AGN fraction and the [OIII] luminosity in our pairs and post-mergers (Figs. 10 and 11), the absolute luminosities are still fairly modest. The correction of the [OIII] luminosity to a bolometric luminosity is highly uncertain, and depends on (among other factors) how (or if) dust is accounted for and whether the AGN is a type I or type II (e.g. Heckman et al. 2005). If we adopt $L_{bol} = 600 \times L([OIII])$, as appropriate for dust-corrected type II AGN (Kauffmann & Heckman 2009), we find typical bolometric luminosities $43 < \log L_{bol} < 45$ erg/s, with very few above this upper bound. The AGN in our merger sample

Figure 11. The enhancement in the [OIII] luminosity for close pairs of AGN galaxies relative to their control sample. The point in the grey shaded box shows the enhancement for galaxies in the SDSS post-merger sample. AGN are classified according to the criterion of Kewley et al. (2001) in order to minimize contamination from star-formation. LINERs are excluded using the criteria of Kewley et al. (2006).

are therefore not high luminosity objects. Whilst it is true that the highest luminosity AGN appear to be dominated by mergers (e.g. Ramos-Almeida et al. 2011; 2012), interactions can clearly result in AGN that can be observed to have relatively low luminosities.

The association between mergers and AGN of different luminosities is complicated by the expectation of highly stochastic accretion rates. It has been shown in several recent works that AGN feeding by a variety of mechanisms may proceed at very low rates for extended periods of time, interspersed with short-lived high accretion rate episodes (Novak, Ostriker & Ciotti 2011; Gabor & Bournaud 2013; Stickley & Canalizo 2013). The enhanced frequency of AGN observed in our sample of pairs indicates that merger-induced AGN triggering can occur well before coalescence (see also Ramos-Almeida et al. 2011), although these AGN typically have modest luminosities. This is in good agreement with the simulations of Stickley & Canalizo (2013) who predict that small amounts of gas are already reaching the nucleus as galaxies recede from their first pericentric passage. In that model, the highest accretion rates are achieved after coalescence, so we might expect that the sample of post-mergers would include some of the highest accretion rate objects.

Although the AGN frequency peaks in the post-merger sample presented here, the bolometric luminosities of post-merger AGN are still modest with values log L_{bol} < 45 erg/s. There are several possible reasons for the lack of high luminosity AGN in post-merger sample. First, despite selection from one of the largest galaxy surveys currently available, the post merger sample is still fairly small, and high luminosity AGN are expected to be both intrinsically rare and short-lived. Not all galaxies may have the requisite gas supply to feed the central supermassive black holes at high fractions of the Eddington rate. Finally, we have argued that the post-mergers in our sample are likely to have only recently (within a few hundred Myrs) coalesced, so there may not yet have been sufficient time for the bulk of gas to reach the nucleus.

The results presented in Section 5, which include both the frequency of AGN and the black hole accretion rate, show both similarities and differences with the conclusions concerning triggered star formation in Section 3. On the one hand, both AGN and star-forming fractions (and the associated intensity of these processes as measured by accretion and star formation rates) show enhancements out to wide separations. The simulations presented in Scudder et al. (2012b) and Patton et al. (2013) indicate that such wide separation enhancements are due to gas flows triggered at pericentric passage that are seen over the course of the merger's dynamical timescale. However, in contrast to the frequency of star forming galaxies, and their SFRs, which increase only modestly post-merger, the AGN frequency and accretion rates rise significantly after coalescence. It seems that whilst both star formation and black hole accretion are enhanced throughout the merger sequence, the former process responds strongly to the interaction already in the early stages, whereas the AGN phase reaches its peak after coalescence. Although simulations have long predicted this general scenario, including the delay between the peak in these two processes (Hopkins 2012), the homogeneous analysis of the large pre- and post-merger samples presented here, has provided the first complete observational picture of mergers.

7 CONCLUSIONS

We have presented a sample of 97 post-merger galaxies selected from the Galaxy Zoo DR7 catalogue of Darg et al. (2010) which we have combined with our existing sample of 10,800 galaxies in spectroscopic close pairs ($r_p \leqslant 80\ h_{70}^{-1}$ kpc, $\Delta V \leqslant 300$ km s^{-1}). Control samples have been constructed by matching in mass, redshift and local environment; several hundred control galaxies are typically identified for every pair or post-merger galaxy. Analysed in a homogeneous way, this combined sample allows us to trace the effects of the interaction throughout the merger sequence and quantify the relative importance of coalescence. Our main conclusions are as follows.

(i) The fraction of star-forming galaxies is enhanced, relative to the control sample, at a similar level for close pairs and post-mergers (Figure 5). Whereas the early interaction phase can apparently turn non-star-forming into star-forming (by our definition) galaxies, the final coalescence has a minimal additional effect. That is, most star-forming post-mergers were likely to already have been star-forming pre-coalescence.

(ii) In the pre-merger phase, we confirm previous results that the central SFR is enhanced by a factor of a few, on average. We also show that the SFR is enhanced outside of the central few kpc by 25 per cent (Figure 6). Post-coalescence, both the inner and outer SFRs are enhanced by a further 40 per cent, leading to a fibre star formation rate enhancement in the post-mergers of a factor of 3.5.

(iii) The fraction of starburst galaxies, with SFR enhancements at least a factor of 10 larger than their controls, peaks in the post-mergers at approximately 20 per cent (Figure 7).

(iv) The star formation that is triggered at coalescence approximately doubles the rate of stellar mass growth, relative to a sample of matched control galaxies (Figure 8).

(v) The metallicities of close pairs are lower than in the control sample out to the widest separations in our sample, with a smooth correlation between metal-deficiency and r_p. The post-mergers are the most metal poor, exhibiting a median Δ [O/H] = −0.09, see Figure 9.

(vi) The persistence and relative elevation of enhanced SFRs and metal deficiencies indicates that the galaxies in our post-merger sample are likely to have coalesced within the last few hundred Myr.

(vii) In contrast to the star-forming fractions, the fraction of AGN in post-mergers is significantly higher than in the close pairs, and higher than the control by a factor of 3.75 (Figure 10). Therefore, although AGN may be triggered pre-coalescence, the final merger has the highest impact on black hole accretion. This is demonstrated directly in Figure 11, where it is shown that the enhancement in the [OIII] luminosity is greatest in the post-mergers.

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