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Spheroidal post-mergers in the local Universe

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ABSTRACT

Galaxy merging is a fundamental aspect of the standard hierarchical galaxy formation paradigm. Recently, the Galaxy Zoo project has compiled a large, homogeneous catalogue of 3373 mergers, through direct visual inspection of the entire SDSS spectroscopic sample. We explore a subset of galaxies from this catalogue that are spheroidal 'post-mergers' (SPMs) - where a single remnant is in the final stages of relaxation after the merger and shows evidence for a dominant bulge, making them plausible progenitors of early-type galaxies. Our results indicate that the SPMs have bluer colours than the general early-type galaxy population possibly due to merger-induced star formation. An analysis using optical emission line ratios indicates that 20 of our SPMs exhibit LINER or Seyfert-like activity (68%), while the remaining 10 galaxies are classified as either star forming (16%) or quiescent (16%). A comparison to the emission line activity in the ongoing mergers from Darg et al. indicates that the AGN fraction rises in the post-mergers, suggesting that *the AGN phase probably becomes dominant only in the very final stages of the merger process.* The optical colours of the SPMs and the plausible mass ratios for their progenitors indicate that, while a minority are consistent with major mergers between two early-type galaxies, the vast majority are remnants of major mergers where at least one progenitor is a late-type galaxy.

Key words: galaxies: elliptical and lenticular, galaxies: evolution, galaxies: formation,

1 INTRODUCTION

Studying how galaxies form and evolve is a fundamental step to better understanding our place in the Universe. The Universe is believed to follow a ΛCDM cosmology (e.g. Blumenthal et al. 1984; Freedman et al. 2001; Efstathiou et al. 2002; Pryke et al. 2002; Spergel et al. 2007) in which $\sim 70\%$ is composed of dark energy, while the remaining $\sim$30% is made of matter, subdivided into baryonic($\sim 5\%$) and dark($\sim 25\%$). This model appears consistent with experimental measurements of the Cosmic Microwave Background (CMB) (e.g. Dunkley et al. 2009; Komatsu et al. 2009) and large scale clustering (e.g. Sanchez et al. 2009). A key feature of the ΛCDM cosmogony is a hierarchical bottom-up formation paradigm, with smaller bodies accreting to form progressively larger ones (White & Rees 1978; Searle & Zinn 1978). Small dark matter halos form first and subsequently merge to form bigger halos (e.g. Peebles 1982; Blumenthal et al. 1984). Baryonic (gas) inflow into the gravitational potential wells created by these halos builds the stellar mass and central black holes in the first galaxies (e.g. Renzini 1977; Fall & Efstathiou 1980; Dalcanton, Spergel & Summers 1997; Mo, Mao & White 1998; Machacek et al. 2001; Schaerer 2003; Venkatesan et al. 2006). Observational and theoretical work has suggested that feedback from supernovae and Active Galactic Nuclei (AGN), powered by the central black holes, may regulate the star formation in galactic systems (e.g. Kauffmann et al. 2003; Di Matteo, Springel &Hernquist 2005; Nesvadba et al. 2006; Schawinski et al. 2007b; Kaviraj et al. 2007b; Alatalo et al. 2011) (and perhaps also in systems in their immediate vicinity, see Shabala et al. 2011) which plausibly produces the observed correlation between the mass of the central black hole and the stellar mass contained in spheroids at present day (e.g. Ferrarese & Merritt 2000).

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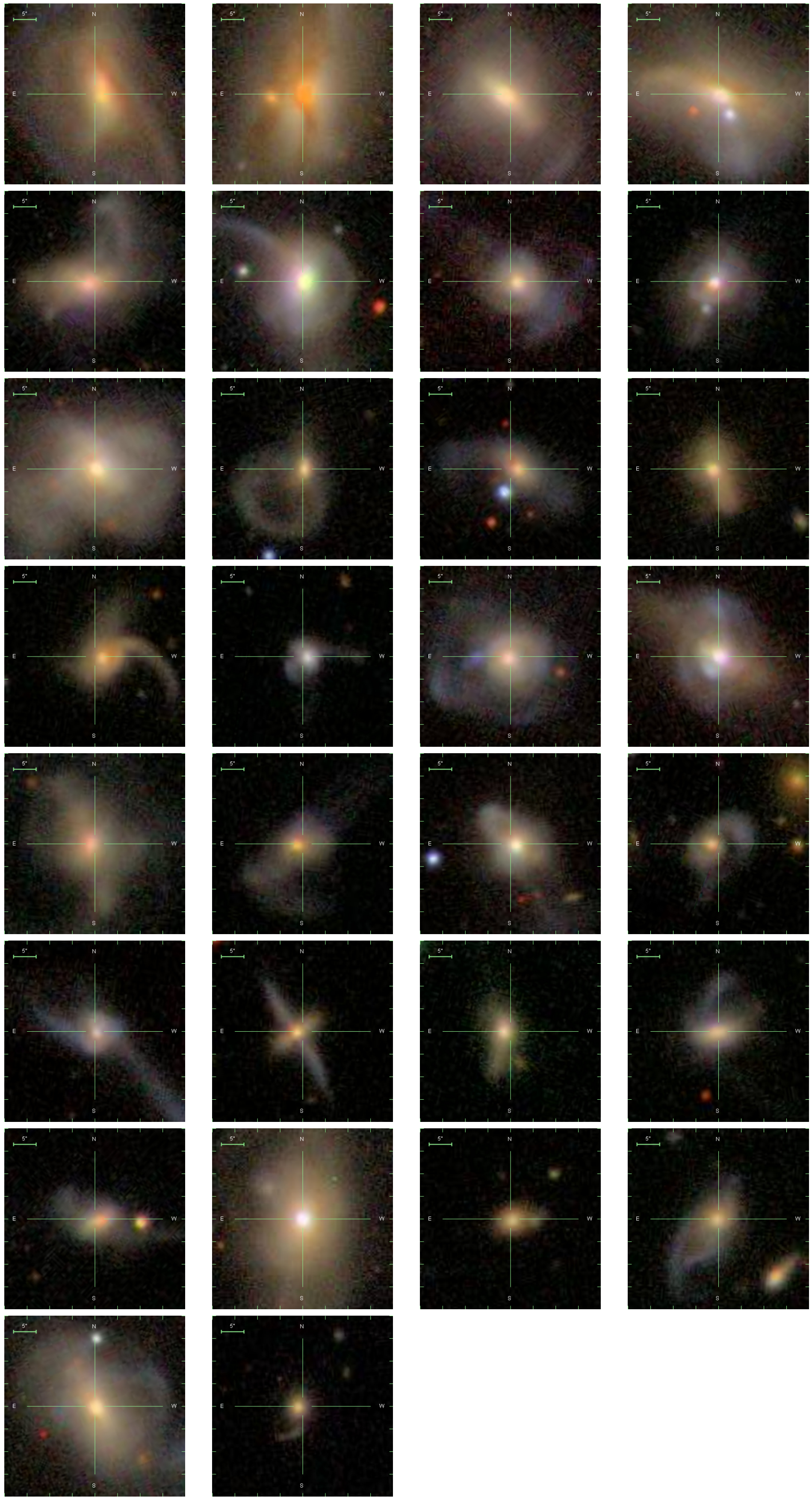

Figure 1. SDSS images of our sample of spheroidal postmergers.

Galaxy merging is thought to be an important driver of the evolution of the visible Universe (e.g. Steinmetz & Navarro 2002). Mergers are believed to drive strong star formation episodes (Mihos & Hernquist 1996), they may contribute to the growth of black holes (Springel, Di Matteo, Hernquist 2005) and they're expected to produce morphological transformations (Toomre 1977). Major mergers between equal mass progenitors are thought to lead to the formation of early-type galaxies, largely independent of the original morphologies of the progenitors (e.g. White & Frenk 1991; Barnes 1992; Cole et al. 2000). Repeated minor mergers appear to be able to produce the same effect (e.g. Bournaud et al. 2007; Naab et al. 2009). Observational evidence for the role of mergers in creating early-type galaxies is suggested by the presence, in many ellipticals, of morphological disturbances such as shells, ripples and tidal tails (e.g. Van Dokkum 2005; Ferreras et al. 2009; Kaviraj 2010a) and evidence for recent merger-driven star formation (Kaviraj et al. 2008, 2009, 2010).

Since mergers are expected to play an important role in the formation of early-type galaxies (Barnes & Hernquist 1996; Bender 1995), an observational study of merger remnants that are likely to end up as early-type galaxies is desirable. A critical issue in studying post-mergers (and indeed mergers in general) is that perhaps the most reliable method for identifying mergers and merger remnants is by visual inspection of galaxy images. Unfortunately this technique becomes very impractical for modern large-scale surveys, such as the *Sloan Digital Sky Survey* (SDSS) which comprises more than one million galaxies in its spectroscopic sample (York et al. 2000). Several automated techniques are able to extract mergers from survey images, all of which have made significant contributions to the merger literature but do have some limitations. For example, merger studies are often based on samples of 'close pairs'[1] but involves an inherent (albeit well-motivated!) assumption that the close-pair system will eventually merge (e.g. Patton et al. 2000). Close-pair techniques can also be biased against minor mergers, since the smaller merger progenitor is often fainter than the spectroscopic limit of the survey in question. Similarly, mergers and merger remnants can be identified via structural parameters such as 'concentration' and 'asymmetry' (e.g. Conselice et al. 2005). While this technique has achieved significant success in probing the merger population in modern surveys (e.g. Conselice et al. 2008), it is difficult to define a parameter space uniquely occupied by mergers and the results typically have to be 'calibrated' against the results of visual inspection (Jogee at al. 2008).

The Galaxy Zoo (GZ; Lintott et al. 2008) project offers a useful alternative. GZ has enlisted 300,000+ volunteers from the general public to morphologically classify, through direct visual inspection, the entire SDSS spectroscopic sample. This includes the compilation of a large homogeneous sample of merging systems in the local Universe (Darg et al. 2010a,b). The Darg et al. merger sample was extracted from the SDSS Data Release 6 (York et al. 2000; Adelman-McCarthy et al. 2008), within the redshift range $0.005 < z < 0.1$. At least one of the two galaxies in each merger has $r < 17.77$ (which is the SDSS spectroscopic limit). The final sample of mergers contains 3373 systems, with mass ratios between 1:1 and 1:10. For a more detailed description of the properties of the sample we refer readers to Darg et al. (2010a). This merger catalogue includes a sample of 'post-mergers', where the system consists of a single object, morphologically disturbed as a result of the recent merger, but in the final stages of relaxation. This study is based on a subset of these post-mergers in which the post-merger system has a dominant bulge, making them plausible progenitors of early-type galaxies.

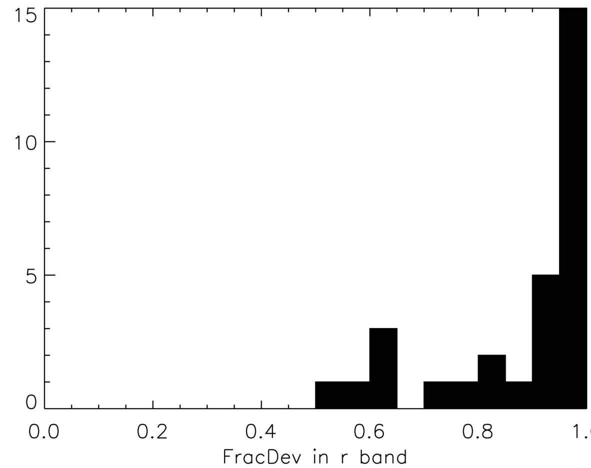

Figure 2. The *fracdev* parameter in the optical r band for our visually selected sample of spheroidal post-mergers. All galaxies have *fracdev* higher than 0.5 (most of them being higher than 0.8) consistent with them being bulge-dominated systems.

The plan for this paper is as follows. In Section 2 we discuss the general properties of the sample. In Section 3 we study the local environments of our SPMs. In Section 4 we discuss their colours and emission line activity while in Section 5 we reconstruct the plausible progenitors of the SPMs. We present our summary in Section 6.

2 THE SAMPLE

We construct a sample of *spheroidal* post-mergers (SPMs) from a parent sample of 370 post-mergers selected by Darg et al. As mentioned above, a postmerger is defined as a *single* object in which the morphological disturbances induced by the recent merger remain visible. In other words a post-merger represents the very final stages of the merger process. We visually re-inspect this postmerger sample to select 30 objects which are clearly bulge-dominated (Figure 1). As a sanity check of our visual classification, we use the SDSS parameter *fracdev* in the optical r band (see Table 1). *Fracdev* indicates the likelihood of the surface brightness profile to be modelled by a pure de Vaucouleurs profile (i.e. *fracdev* ~ 1 indicates a pure bulge, while *fracdev* ~ 0 represents a purely exponential or disk-like profile). Past work (e.g. Kaviraj et al. 2007a) has successfully used this parameter as a measure of morphology in large galaxy samples. In Figure 2 we plot the *fracdev* in the r band of our sample. All our SPMs have a *fracdev* greater than 0.5 (i.e. they are domi-

[1] Close pairs are normally defined using a projected distance of 30 kpc and a line of sight velocity differential ($\Delta z \leqslant 500$ km s^{-1}) (Patton et al. 2000)

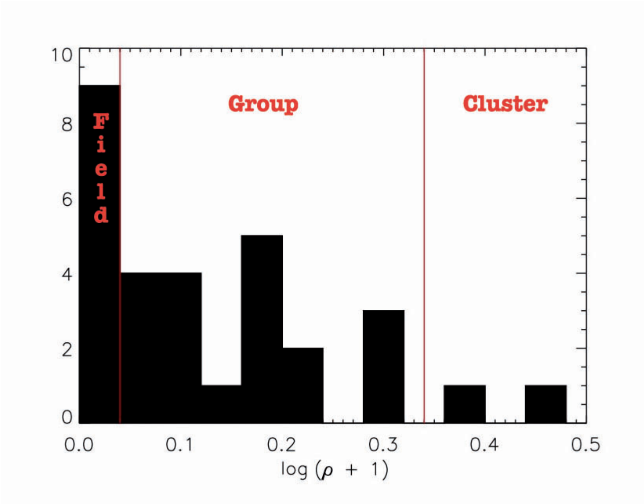

Figure 3. The values of the environment parameter (ρ) for the sample: two galaxies in our sample inhabit clusters ($log(\rho+1) > 0.30$), with the rest split between groups ($0 < log(\rho+1) < 0.30$) and the field. See text for details.

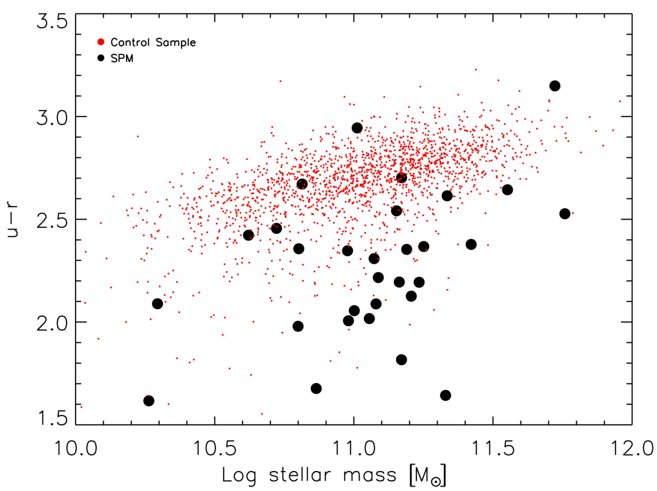

Figure 4. The $(u-r)$ colour-mass relation of the spheroidal postmergers (large black circles), compared to a control sample of early-type galaxies from the SDSS (red dots).

nated by the 'bulge-like' profile), with most of them higher than 0.8, which is consistent with the results of our visual classification. Note that not all postmergers with high values of *fracdev* from the original sample of 370 were in fact bulge-dominated when inspected visually, a further example of the utility of employing visual inspection in conjunction with automatic techniques.

Following the estimated completeness of the Darg et al. merger sample, we expect the completeness of our SPM sample to be around 80%.

3 LOCAL ENVIRONMENTS

We begin by exploring the local environments of our SPMs, using the environment parameter (ρ_g) defined by Schawinski et al. (2007a). This is defined as a weighted sum of all the

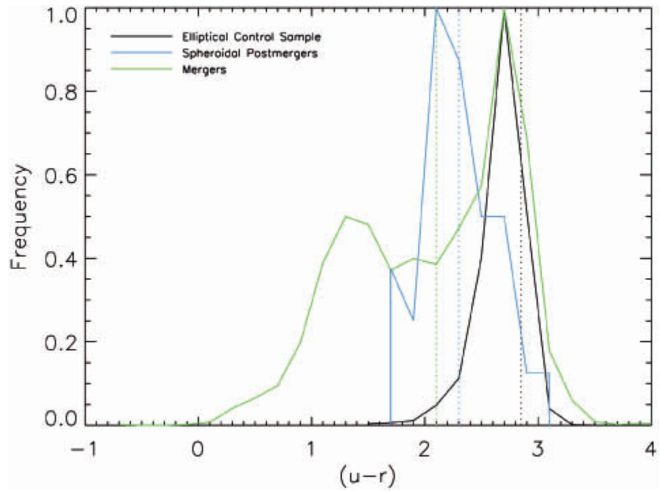

Figure 5. Histogram of $(u-r)$ colour of the SPMs, ongoing mergers from the catalogue of Darg et al. and a control sample of early-type galaxies from the SDSS. The SPMs lie intermediate between the ongoing mergers and early-type control sample, indicating that the star formation activity peaks before the post-merger phase. The dotted lines are the median values for the populations.

neighbours within the ellipse

$$\left(\frac{r_a}{3\sigma}\right) + \left(\frac{r_z}{3c_z\sigma}\right) \leqslant 1 \tag{1}$$

where r_a is the distance on the sky in Mpc to each surrounding galaxy, r_z is the distance along the line-of-sight in Mpc to each surrounding galaxy, and σ is the radius. The parameter c_z scales the value of σ along the line of sight to compensate for the 'finger of god' effect (see Schawinski et al. 2007 for more details)[2]. According to this definition a galaxy with $\rho_g = 0$ typically has no neighbours in a σ radius. Values in the range $0<\rho_g<0.1$ are consistent with a field environment. Galaxies with $0.1<\rho_g<1$ are in a group environment, while anything larger typically corresponds to clusters. We find that two galaxies in our SPM sample inhabit clusters ($\rho_g > 1$), while the rest are split between groups and the field. This result is expected since the high peculiar velocities of the galaxies in dense environments such as clusters make collisions unlikely. Similarly, in very sparse environments there are not enough galaxies around to produce many merger events, so a post-merger population spread between intermediate and low-density environments is reasonable. The environment parameter values for the sample are shown in Figure 3.

4 COLOURS AND EMISSION LINE ACTIVITY

In Figures 4 and 5 we compare the colours of the SPMs to both an early-type control sample and the *ongoing* mergers from Darg et al. The colours are K-corrected according

[2] The finger of god is an effect in observational cosmology that causes clusters of galaxies to be elongated in redshift space, with an axis of elongation pointed towards the observer. It is caused by a Doppler shift associated with the peculiar velocities of galaxies in a cluster.

SDSS ID	RA	DEC	FracDev in r	ρ	Redshift	Log(Mass)
587726102026453183	227.770	4.293	0.799	0.536	0.0420	11.552
587726102027239592	229.454	4.162	0.628	0.609	0.037	11.722
587731521205567501	132.978	40.835	1	1.08519	0.029	11.153
587731681194868806	139.212	45.700	0.948	0.084	0.026	11.073
587732484342415393	130.937	35.828	0.638	1.942	0.054	11.002
587733431923703839	253.789	26.664	0.940	1.017	0.035	11.163
587734948595236905	160.265	11.096	1	1.019	0.053	11.206
587735663161442343	153.992	39.243	1	0.547	0.0627	10.865
587735665845403787	221.437	51.580	0.894	0.0156	0.030	11.235
587735696984571992	201.726	56.889	1	0.207	0.090	11.172
587736585513795652	244.425	25.205	0.950	0.043	0.0311	10.294
587736586036969554	211.414	40.032	1	0.046	0.084	11.335
587738409785557168	143.447	10.811	0.711	0.00676	0.085	11.758
587738946141552732	169.385	37.963	0.943	0.098	0.096	10.799
587738947747053602	154.640	36.224	0.851	0.591	0.054	11.056
587739707951808602	227.963	23.151	1	0	0.052	11.171
587741533323526200	173.781	29.891	0.857	0.103	0.046	10.980
587741533859414124	171.142	30.095	1	0.148	0.055	10.722
587741600963690567	198.656	26.123	1	0.079	0.074	11.251
587741708326469917	128.289	15.398	1	0.219	0.076	10.802
587741709954121847	168.418	27.241	0.658	0.453	0.037	10.263
587742062680015040	176.183	23.162	1	0	0.048	10.621
587744874792222779	137.156	14.122	1	0.158	0.0882	11.080
588007005789683827	196.060	65.345	0.598	0.412	0.083	11.087
588013382183944595	119.951	27.838	0.536	0.0442	0.067	10.977
588015508746338312	31.566	-0.2914	1	0.529	0.0426	11.329
588017565490872652	187.554	11.770	0.922	1.459	0.089	11.012
588017705071214745	164.196	12.762	0.963	0.5035	0.092	11.421
588017978367934481	218.326	34.734	0.996	0.288	0.034	11.190
588017978895892603	193.458	39.738	1	0.259	0.092	10.814

Table 1. SDSS ID, RA, DEC, r-band *fracdev*, environment parameter ρ, spectroscopic redshift and stellar mass for our sample of postmergers. Stellar masses are estimated using the calibrations of Bell et al. (2003)

to the technique devised by Blanton (2007) using the IDL routine `KCORRECT`(version 4.2). Stellar masses are estimated using the calibrations of Bell et al. (2003). The early-type control sample is constructed using the GZ early-type galaxy catalogue restricted to the redshift and magnitude range of the Darg et al. mergers (see Darg et al. 2010a). The vast majority (85%) of our SPM sample have bluer colours than the mean colours of the early-type control population (Figure 5). These blue populations are likely to contain both young stars formed in the recent merger as well as remnants of the blue stellar populations in the original progenitors. However, they are typically not bluer than the population of ongoing mergers from Darg et al. (2010), which suggests that the star-formation rate is subsiding in the postmerger phase. While there is some debate on exactly when the star formation activity peaks during the merger process (Barton et al. 2000; Lambas et al. 2003; Nikolic, Cullen & Alexander 2004; Di Matteo, Springel &Hernquist 2005; Schawinski et al. 2009b), our results suggest that it peaks prior to the final coalescence of the merger progenitors. We use optical emission-line ratios (see e.g. Baldwin, Phillips & Terlevich 1981) to explore the emission-line activity in the SPM sample and compare it to what is found in the control sample of early-type galaxies and the ongoing mergers from Darg et al. Emission lines are calculated using the public GANDALF code[3] (Sarzi et al. 2006).

The majority of the SPMs display Seyfert-like emission (42%) with the rest being either LINERs (26%), star-forming (16%), or quiescent (16%) objects. In comparison, the dominant emission-line type in the ongoing mergers is the star-forming population, while the dominant type in the control early-types are quiescent objects. Together with the higher fraction of LINERs in the SPMs (which are likely to be post-starburst galaxies, see e.g. Sturm et al. (2006); Sarzi et al. (2010)) and since it has not been possible to identify blue Compton-thick AGN in the local universe (Schawinski et al. 2009b) our results suggest that these objects have gone through a gradual transition from being dominated by star formation in the merger phase to AGN activity in the post-merger phase, followed by quiescence when the objects have transitioned to being relaxed spheroids. While the small number of SPMs makes a robust conclusion difficult, our results suggest that, not only is there a delay between the onset of star formation and AGN activity, in agreement with several studies in the literature (Schawinski

[3] GANDALF is a simultaneous emission and absorption lines fitting algorithm, designed to separate the relative contribution of the stellar continuum and nebular emission in the spectra of nearby galaxies, while measuring the gas emission and kinematics. This method has been used to derive the ionised-gas maps and kinematics of the SAURON sample (Sarzi et al. 2006)

et al. 2007b; Wild et al. 2010; Darg et al. 2010b), *but that the peak of AGN activity may coincide with the post-merger phase of the merger process.* Note that, in this case, the delay between the onset of star formation and AGN activity could be expected to be around the coalescence timescale of the merger, which is around 0.5-1 Gyr for a major merger (Springel, Di Matteo, Hernquist 2005; Lotz et al. 2008). This appears consistent with the time delays derived from spectral fitting in recent work (Schawinski et al. 2007b; Wild et al. 2010; Darg et al. 2010b).

5 RECONSTRUCTING THE PROGENITORS

In this section we explore the plausible progenitors of the SPM sample. Under the reasonable assumption that the sample of ongoing mergers in Darg et al. are the progenitors of the SPMs, we first search for merging systems which have a summed mass within 0.3 dex of the mass of the SPM in question. We use 0.3 dex as the tolerance because it is the typical mass error. We assume that major mergers of all morphological types (elliptical-elliptical, elliptical-spiral and spiral-spiral) produce spheroids (e.g. Khochfar & Silk 2006) and that, from simple dynamical considerations, all minor mergers whose major partner is an elliptical will create a spheroid. Note that the merger catalogue of Darg et al. is not expected to be biased against minor mergers with mass ratios between 1:4 and 1:10. The median mass ratios for the SPMs, under these assumptions, are between 1:1.5 to 1:3, with a tail to lower values, suggesting that these systems are typically remnants of major mergers.

To explore the morphologies of the progenitors further, we make a simple comparison of the SPM colours to the expected colour of a passively evolving old population, typical of early-type galaxies at the present day (e.g. Bower et al. 1992; Bender 1997; Springel, Di Matteo, Hernquist 2005; De Lucia et al. 2006; Kormendy et al. 2009). The colours of the SPMs suggest that, in most of these galaxies, a significant minority of the stellar population is likely to have formed in the recent merger-driven burst of star formation.

To explore the star formation histories of the SPMs further, we study simple models in which a young population, formed in an instantaneous starburst, is superimposed on an old population that is also formed in an instantaneous event. We assume that the old population is formed at $z = 3$ and has solar metallicity, since this is typical of the old, metal-rich stellar populations that dominate nearby early-type galaxies (e.g. Trager et al. 2000). The free parameters are the age, mass fraction and metallicity of the recent (young) starburst and the average dust content ($E_{(B-V)}$) of the system. We explore ages for the recent starburst between 0.2 and 0.6 Gyrs, which bracket the coalescence timescales for major mergers in the literature (Springel, Di Matteo, Hernquist 2005; Lotz et al. 2008). We explore metallicities between 0.75 and 2.5 $Z_{\odot}$ which is the scatter in the mass-metallicity relation of galaxies in our mass range in the local Universe Tremonti et al. (2004). We assume a median $E_{(B-V)}$ of 0.05, derived by recent UV-optical studies of nearby early-type galaxies (Kaviraj et al. 2007b; Schawinski et al. 2007b).

Early-type galaxies are largely devoid of gas. Gas fractions in early-types within the mass range considered in this study are typically (much) less than 5% (Kannappan 2004; Young 2002). Mergers that have two early-type progenitors are therefore very unlikely to produce more than 5% in mass fraction of young stars. By comparing the $(u-r)$ and $(g-r)$ colours of the simple models with the observed colours of the SPMs, we estimate how many of our postmergers may be the product of mergers between two early-types and therefore how many are likely to require at least one late-type progenitor. Considering the range of parameters described above we find that ∼55% are likely to have formed in a merger involving a gas-rich i.e. late-type galaxy. Figure 7 demonstrates this analysis for a specific model in the young starburst has an age of 0.5 Gyr, solar metallicity and an $E_{(B-V)}$ of 0.05.

6 SUMMARY

We have studied a sample of 30 bulge-dominated or spheroidal post-mergers (SPMs) in the local Universe which are, by virtue of their morphology, plausible progenitors of early-type galaxies. These galaxies are a subset of Darg et al. (2010a)) who have produced a large, homogeneous catalogue of mergers, through direct visual inspection of the entire SDSS spectroscopic sample using the Galaxy Zoo project.

The vast majority of the SPMs inhabit low-density environments (groups and the field), consistent with the expectation that the high peculiar velocities in high-density environments make conditions difficult for galaxy merging. Our SPM sample is generally bluer that a control sample of early-type galaxies but redder, on average, than the merging population, indicating that the peak of star formation activity takes place during the merger phase. 84% of the SPMs exhibit emission-line activity. 42% show Seyfert-like emission, 26% are LINERs and 16% are classified as star-forming. In contrast, the control sample of early-type galaxies is dominated by quiescent objects, while the mergers are dominated by star-forming galaxies. The rise in the AGN fraction in the post-merger phase (compared to the mergers) suggests that the AGN phase probably becomes dominant only in the very final stages the merging process. Comparison of the SPMs to the ongoing mergers in the Darg et al. sample indicates that they are likely to be the remnants of major mergers.

Since major mergers coalesce on timescales around 0.5 Gyr, we have compared the colours of the SPMs to models in which a young stellar population with an age of 0.5 Gyr is superimposed on an old population that forms at $z = 3$ (since the bulk of the stars in early-type galaxies are known to be old).We have found that, under these assumptions, the vast majority of the SPMs are likely to have formed more than 5% of their stellar mass in the recent merger driven burst. Since early-type galaxies themselves are rather gas-poor objects, our results indicate that ∼55% of the SPMs are products of major mergers in which at least one of the progenitors is a late-type galaxy.

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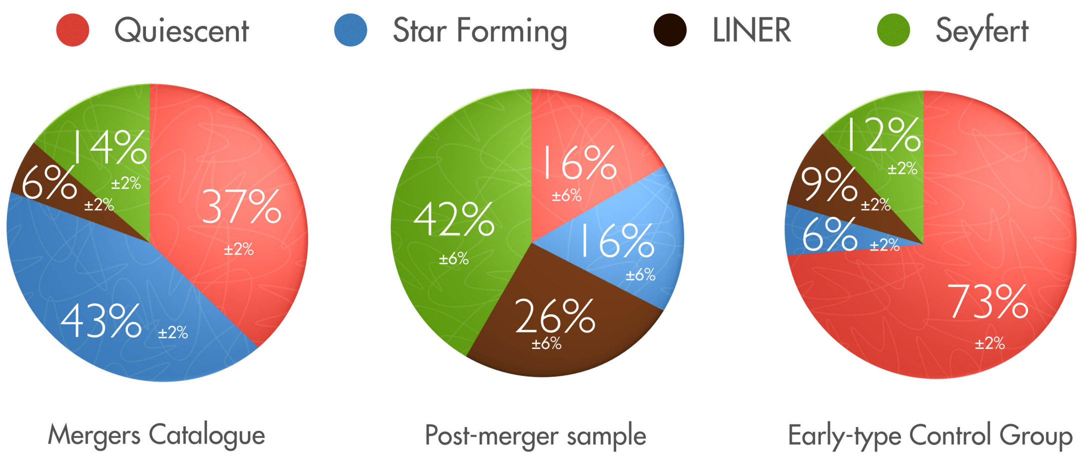

Figure 6. Emission-line analysis of the SPMs compared to the ongoing mergers from Darg et al., and a control sample of early-type galaxies from the SDSS. The dominant emission-line type in the ongoing mergers are star-forming galaxies, while the dominant type in the SPMs and early-type controls are AGN and quiescent galaxies respectively. The AGN phase appears to dominate the postmerger phase in the morphological sequence.

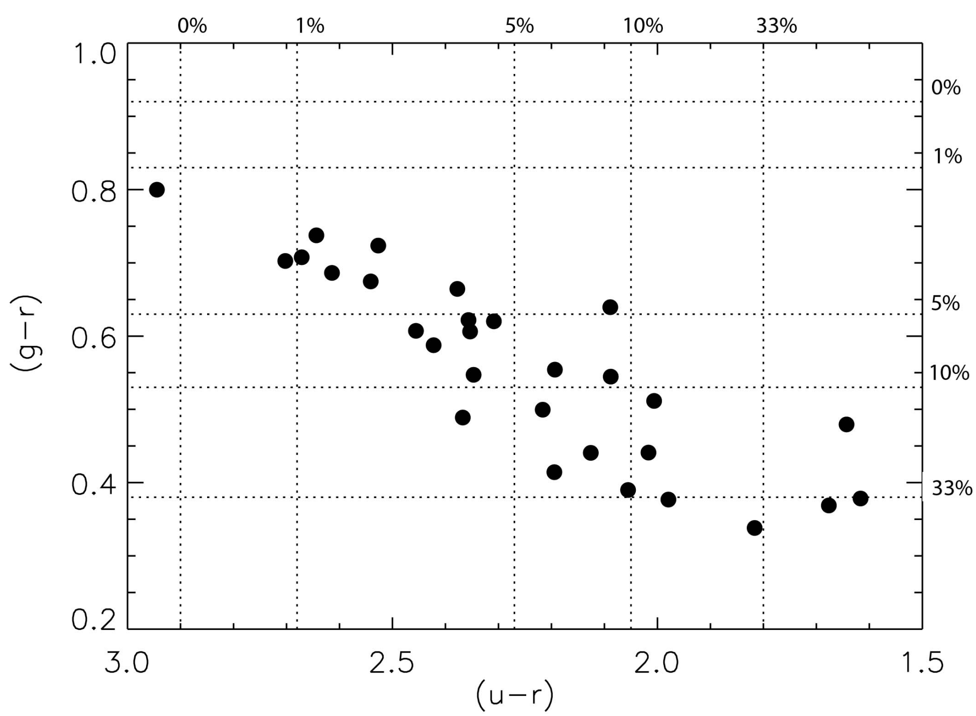

Figure 7. Comparison of the colours of the spheroidal postmergers to a simple model, designed to approximate the stellar content in these galaxies. The model is parametrised by two instantaneous starbursts, the first fixed at an age of 10 Gyr (since the bulk of the stars in early-type galaxies form at high redshift). The second burst is assumed to take place 0.5 Gyr in the past (the typical coalescence timescale of major mergers). The mass fraction contributed by this young population is indicated by the horizontal and vertical lines. Note that we assume solar metallicity and no dust in the models.

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REFERENCES

Adelman-McCarthy et al. 2008, ApJS, 175, 297
Alatalo, K., et. al., 2011 ApJ, 735, 88
Baldwin, J. A., Phillips, M. M., & Terlevich, R., 1981, PASP, 93, 5
Barnes, J. E. 1992, ApJ, 393, 484
Barnes, J. E., & Hernquist, L., 1996 Ap. J. 471, 115
Barton, E. J., Geller M. J., & Kenyon S. J. 2000, ApJ, 530, 66
Bell, E., et al., 2003, ApJS, 149, 289
Bell, E., et al., 2004, ApJ, 608, 75
Bender, R., in IAU Symp. 171: New Light on Galaxy Evolution, eds. R. Bender and R. L. Davies (IAU, 1995)
Bender, R., Structure formation and ages of elliptical galaxies, in ASP Conf. Ser. 116: The Nature of Elliptical Galaxies; 2nd Stromlo Symposium (ASP, 1997).
Blanton, M. R., 2007, ApJ, 133, 734
Blumenthal, G.R., Faber, S.M., Primack, J.R., Rees, M.J. 1984, Nat, 311, 517
Bournaud, F., Jog, C. J., Combes, F., 2007, A&A, 476, 1179
R. G. Bower, J. R. Lucey and R. Ellis, Mon. Not. R. Astron. Soc. 254, 589 (1992).
Cole, S., Lacey, C., Baugh, C. M., & Frenk, C. S. 2000, MNRAS, 319, 168
Conselice, C. J., Blackburne, Jeffrey A., Papovich, C., 2005 ApJ, 620, 564
Conselice C. J., Rajgor S., Myers R., 2008, MNRAS, 386, 909
Cox, T. J., Dutta, S. N., Matteo, T. D., Hernquist, L., Hopkins, P. F., Robertson, B., & Springel,V. , 2006, ApJ, 650, 791
Croton, D.J., et al, 2006, MNRAS, 365, 11
Crockett, R. M., et al, 2011, ApJ, 727, 115
Dalcanton, J. J., Spergel, D. N., Summers, F. J., 1997, ApJ, 482, 659
Darg, D. et al. 2010, MNRAS, 401, 1043
Darg, D. et al. 2010, MNRAS, 401, 1552
De Lucia, G., Springel, V., White, S. D. M., Croton, D., Kauffmann, G., 2006, MNRAS, 366, 499
Di Matteo, T., Springel, V., Hernquist, L., 2005, Nat, 433, 604
Dressler, A., 1980 ApJ, 236, 351
Dunkley, J., et al., 2009 ApJS 180, 306329.
Efstathiou, G., et al., 2002, MNRAS, 330, L29
Eggen, O. J., Lynden-Bell, D., Sandage, A. R. ,1962, ApJ, 136, 748
Fall S.M., Efstathiou G., 1980, MNRAS, 193, 189
Ferrarese, L.; Merritt, D. 2000, ApJ, 539, 9
Ferreras, I., Lisker, T., Pasquali, A., Kaviraj, S., 2009, MNRAS, 395, 554
Foster, P. N., Boss, A. P., 1996, ApJ, 468, 784
Freedman, W. L., et al., 2001, ApJ, 553, 47
Hatton, S., Devriendt, J. E. G., Ninin, S., Bouchet, F. R., Guiderdoni, B., & Vibert, D., 2003, MNRAS, 343, 75
Heger, A., Woosley, S. E., 2002, ApJ, 567, 532
Jogee S., et al., 2008, arXiv:0802.3901
Kannappan S.J., 2004, ApJ, 611, 89
Kauffmann, G., White, S. D. M., Guiderdoni, B., 1993, MNRAS, 264, 201
Kauffmann G., Heckman T.M., Tremonti C., et al., 2003,MNRAS, 346, 105
Kaviraj, S., et al., 2007, ApJS, 173, 619
Kaviraj S., Kirkby L. A., Silk J., Sarzi M., 2007, MNRAS, 382, 960
Kaviraj, S. et al., 2008, MNRAS, 388, 67
Kaviraj, S., Peirani, S., Khochfar, S., Silk, J., & Kay, S. 2009, MNRAS, 394, 1713
Kaviraj, S., Tan, K., Ellis, R. S., Silk, J., 2010, arXiv:1001.2141
Kaviraj, S., 2010, MNRAS, 406, 382
Kaviraj, S., 2010, MNRAS, 408, 170
Kennicutt, R., 1998, ARA&A, 36, 189
Khochfar, S., Silk, J., 2006, MNRAS, 370, 902
Khochfar, S., Silk, J., 2009, MNRAS, 397, 506
Komiya, Y., et al., 2009, ApJ, 696, 79
Komatsu, E., et al., 2009 ApJS 180, 330.
Kormendy, J., Fisher, D. B., Cornell, M. E., Bender, R., 2009, ApJS, 182, 216
Kriek, M., van Dokkum, P. G., Franx, M., Illingworth, G. D., & Magee, D. K., 2009, ApJ, 705, 71
Lambas, D. G., Tissera, P. B., Alonso, M. S., & Coldwell, G., 2003, MNRAS, 346, 1189
Larson, R. B., 2003, RPPh, 66, 1651
Lintott C. J. et al., 2008, MNRAS, 389, 1179
Lotz, J. M., Jonsson, P., Cox, T. J., Primack, J. R., 2008, MNRAS, 391, 1137
Machacek, M. E., Bryan, G. L., & Abel, T., 2001, ApJ, 548, 509
Masters, K. et al., 2010, MNRAS, 487
Mihos, C.J. & Hernquist, L., 1996, ApJ, 464, 641
Milosavljevic, M.; Merritt, D. 2003, AIPC, 686, 201
Mo H. J., Mao, S., White, S. D. M., 1998, MNRAS, 295, 319

Naab, T., Johansson, P. H., Ostriker, J. P., 2009, ApJ, 699, 178
Nesvadba, N., et al., 2006 ApJ, 650, 693
Nikolic, B., Cullen, H., & Alexander, P., 2004, MNRAS, 355, 874
Noguchi, M., 1999, ApJ, 514, 77
Papovich, C., Dickinson M., Giavalisco M., Conselice C.J., Ferguson H. C., 2005, ApJ, 631, 101
Panter, B., Jimenez, R., Heavens, A. F., Charlot, S., 2007, MNRAS, 378, 1550
Patton, D. R., Carlberg, R. G., Marzke, R. O., Pritchet, C. J., da Costa, L. N., Pellegrini, P. S., 2000, ApJ, 536, 153
Patton, David R., Ellison, S. L., Simard, L., McConnachie, A. W., Mendel, J. T., 2010, arXiv1010.5778P
Peebles P., 1982, ApJ, 263, L1
Pryke, C., Halverson, N. W., Leitch, E. M., Kovac, J., Carlstrom, J. E., Holzapfel, W. L., Dragovan, M. 2002, ApJ, 568, 46
Renzini, A., 1977, ASSE Conference, 151
Richstone, D., et al., 1998, Nature, 385, A14
Robertson, B., et al., 2006, ApJ, 645, 986
Ruzkowsky, M., Springel, V., 2009, ApJ, 696, 1094
Sanchez, A.G., Crocce, M., Cabre, A., Baugh, C.M., Gaztanaga, E., 2009, MNRAS, 400 1643
Sarzi, M. & the SAURON team, 2006, MNRAS, 366, 1151
Sarzi, M. et al., 2010, MNRAS, 402. 2187
Shabala, S. S., Kaviraj, S., Silk, J., 2011, MNRAS, 336
Schaerer, D., 2003, A&A, 397, 527
Schawinski, K., et al., 2007, ApJS, 173, 512
Schawinski, K., et al., 2007, MNRAS, 382, 1415
Schawinski, K., et al., 2009, MNRAS, 396, 818
Schawinski, K., et al., 2009, ApJ, 692, 19
Schawinski, K. et al., 2010, ApJ, 711, 284
Searle, L., Zinn, R., 1978, ApJ, 225, 357
Shakura, N.I., & Sunayev, R.A., 1973, A&A, 24, 337
Spergel, D. N., et al. 2007 ApJS 170 377
Springel, V., Di Matteo, T. & Hernquist, L., 2005, ApJ, 620, 79
Steinmetz, M., & Navarro, J. 2002 New Astronomy, 7, 155
Strateva, I. V., et al., 2001, ApJ, 122, 1861
Sturm, E. et al., 2006, ApJ, 653, 13
Toomre, A., 1977 ESPG Conf. 401 T
Trager, S. C., Faber, S. M., Worthey, G., & Gonzalez, J. J. 2000, AJ, 119, 1645
Tremonti, C. A., et al. 2004 ApJ 613 898
Van Dokkum, P. G., 2005, ApJ ,130, 2647
Venkatesan, A., Nath & Shull 2006 ApJ 640 31
Verma, A. et al., 2007, MNRAS, 377, 1024
Wang, J. L. et al., 2006, ApJ, 649: 722
White, S. D. M., & Frenk, C. S., 1991, ApJ, 379, 52
White, S.D.M., Rees, M.J., 1978, MNRAS, 183, 34
Wild V., Kauffmann G., Heckman T., Charlot S., Lemson G., Brinchmann J., Reichard T., Pasquali A., 2007, MNRAS, 381, 54
Wild, V., Heckman, T., & Charlot, S. 2010, MNRAS, 405, 933
York D. G., Adelman, J., Anderson, J. E., 2000, AJ, 120, 1579
Young, L. M. 2002, AJ, 124, 788
Zeldovich, Ya. B. 1970, A&A, 5, 84