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 Sloan Digital Sky Survey 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 per cent), while the remaining 10 galaxies are classified as either star forming (16 per cent) or quiescent (16 per cent). A comparison to the emission-line activity in the ongoing mergers from Darg et al. indicates that the active galactic nuclei (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, cD – galaxies: evolution – galaxies: formation – galaxies: interactions.

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 cold dark matter (ΛCDM) cosmology (e.g. Blumenthal et al. 1984; Freedman et al. 2001; Efstathiou et al. 2002; Pryke et al. 2005; Spergel et al. 2007) which is composed of dark energy, while the remaining 70 per cent is made of matter, subdivided into baryonic (5 per cent) and dark (25 per cent). This model appears consistent with experimental measurements of the cosmic microwave background (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 cosmology is a hierarchical bottom-up formation paradigm, with smaller bodies accreting to form progressively larger ones (Searle & Zinn 1978; Kauffmann, White & Guideroni 1993). Baryonic (gas) inflow into the gravitational potential wells created by these haloes builds the stellar mass and central black holes in the first galaxies (e.g. Zinn 1977; Fall & Efstathiou 1980; Spergel & Summers 1997; Mo, Mao & White 1998; Machacek, Bryan & Abel 2001; Schaerer 2003; Venkatesan, Nath & Shull 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). 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; Kaviraj et al. 2007b; Schawinski et al. 2007b; Alatalo 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).

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

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(Mihos & Hernquist 1996), they may contribute to the growth of black holes (Springel, Di Matteo & Hernquist 2005) and they are 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, Jog & Combes 2007; Naab, Johansson & Ostriker 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, 2011; Kaviraj 2010b; Schawinski 2009a).

Since mergers are expected to play an important role in the formation of early-type galaxies (Bender 1995; Barnes & Hernquist 1996), 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, Adelman & Anderson 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’ 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, Rafter & Myers 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 et 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 the 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.

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 post-merger 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 post-merger sample to select 30 objects which are clearly bulge-dominated (Fig. 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 disc-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 Fig. 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 dominated 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 post-mergers 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 per cent.

3 LOCAL ENVIRONMENTS

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

$$\left(\frac{r_g}{3\sigma}\right) + \left(\frac{r_s}{3\sigma}\right) \leq 1,$$

where r_g is the distance on the sky in Mpc to each surrounding galaxy, r_s is the distance along the line of sight in Mpc to each surrounding galaxy, and σ is the radius. The parameter c_s scales the value of σ along the line of sight to compensate for the ‘finger of god’ effect (see Schawinski et al. 2007a, for more details).2 According to this definition, a galaxy with ρg = 0 typically has no neighbours in a σ radius. Values in the range 0 < ρg < 0.1 are consistent with a field environment. Galaxies with 0.1 < ρg < 1 are in a group environment, while anything larger typically corresponds to clusters. We find that two galaxies in our SPM sample

1 Close pairs are normally defined using a projected distance of 30 kpc and a line-of-sight velocity differential (Δz ≤ 500 km s⁻¹) (Patton et al. 2000).

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.
Figure 1. SDSS images of our sample of SPMs.
Table 1. SDSS ID, RA, Dec., \( r \)-band fracdev, environment parameter \( \rho \), spectroscopic redshift and stellar mass for our sample of post-mergers. Stellar masses are estimated using the calibrations of Bell et al. (2003).

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

inhabit clusters (\( \rho > 1 \)), 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 Fig. 3.

4 COLOURS AND EMISSION-LINE ACTIVITY

In Figs 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.

Figure 3. The values of the environment parameter (\( \rho \)) 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.
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, Lucey & Ellis 1992; Bender 1997; Springel et al. 2005; De Lucia et al. 2006; Kormendy et al. 2009). The colours of the SPMs suggest that, in most of these galaxies, a significant fraction of the stellar population is older than the age of the universe, consistent with previous studies (e.g. Sturm et al. 2006; Sarzi et al. 2010) and with the expected behaviour of galaxy mergers.

The colours of the SPMs display Seyfert-like emission (42 per cent) with the rest being either LINERs (26 per cent), star-forming (16 per cent), or quiescent (16 per cent) 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 (see Fig. 5). 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 et al. 2007b; Darg et al. 2010b; Wild, Heckman & Charlot 2010), but also 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 time-scale of the merger, which is around 0.5–1 Gyr for a major merger (Springel et al. 2005; Lotz et al. 2008). This appears consistent with the time delays derived from spectral fitting in recent work (Schawinski et al. 2007b; Darg et al. 2010b; Wild et al. 2010).

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 ionized-gas maps and kinematics of the SAURON sample (Sarzi et al. 2006).
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 Gyr, which bracket the coalescence time-scales for major mergers in the literature (Springel et al. 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 per cent (Young 2002; Kannappan 2004). Mergers that have two early-type progenitors are therefore very unlikely to produce more than 5 per cent 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 post-mergers 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 $\sim 55$ per cent are likely to have formed in a merger involving a gas-rich i.e. late-type galaxy. Fig. 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 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 GZ 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 than 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 per cent of the SPMs exhibit emission-line activity. 42 per cent show Seyfert-like emission, 26 per cent are LINERs and 16 per cent 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 of 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 time-scales 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 per cent of their stellar mass in the recent merger-driven burst. Since early-type galaxies themselves are rather gas-poor objects, our results indicate that $\sim 55$ per cent 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 7. Comparison of the colours of the SPMs to a simple model, designed to approximate the stellar content in these galaxies. The model is parametrized 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 time-scale 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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