Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 24 August 2011 (MN LATEX style file v2.2)

Tidal dwarf galaxies in the nearby Universe

Sugata Kaviraj[1,2⋆], Daniel Darg[2], Chris Lintott[2], Kevin Schawinski[3,4] and Joseph Silk[2]

[1] *Blackett Laboratory, Imperial College London, London SW7 2AZ, UK*
[2] *Department of Physics, University of Oxford, Keble Road, Oxford, OX1 3RH, UK*
[3] *Department of Physics, Yale University, New Haven, CT 06511, USA*
[4] *Einstein Fellow*

24 August 2011

ABSTRACT
We present a statistical observational study of the tidal dwarf (TD) population in the nearby Universe by exploiting a large, homogeneous catalogue of galaxy mergers compiled from the *Sloan Digital Sky Survey*. 95% of TD-producing mergers involve two spiral progenitors (typically both in the blue cloud), while most remaining systems have at least one spiral progenitor. The fraction of TD-producing mergers where both parents are early-type galaxies is less than 2%, suggesting that TDs are unlikely to form in such mergers. The bulk of the TD-producing systems inhabit a field environment and have mass ratios greater than ∼1:7 (the median value is 1:2.5). TDs forming at the tidal-tail tips are ∼4 times more massive than those forming at the base of the tails. TDs have stellar masses that are less than 10% of the stellar masses of their parents (the median is 0.6%) and lie within 15 optical half-light radii of their parent galaxies. The TD population is typically bluer than the parents, with a median offset of ∼0.3 mag in the $(g-r)$ colour and the TD colours are not affected by the presence of AGN activity in their parents. An analysis of their star formation histories indicates that TDs contain both newly formed stars (with a median age of ∼30 Myrs) and old stars drawn from the parent disks, each component probably contributing roughly equally to the stellar mass of the object. Thus TDs are not formed purely through gas condensation in tidal tails but host a significant component of old stars from the parent disks. Finally, an analysis of the TD contribution to the observed dwarf to massive galaxy ratio in the local Universe indicates that ∼6% of dwarfs in nearby clusters may have a tidal origin, if TD production rates in nearby mergers are representative of those in the high-redshift Universe. Even if TD production rates at high redshift were several factors higher, it seems unlikely that the entire dwarf galaxy population today is a result of merger activity over the lifetime of the Universe.

Key words: galaxies: dwarf - galaxies: interactions - galaxies: starburst - galaxies: formation - galaxies: active

1 INTRODUCTION

Galaxy mergers are a key driver of cosmological evolution, stimulating intense star formation episodes (e.g. Barnes & Hernquist 1992a), fuelling the growth of central black holes (e.g. Springel et al. 2005) and altering the morphological mix of the visible Universe (e.g. Toomre 1977; Steinmetz & Navarro 2002). While much of the literature has focussed on phenomena in the central regions of merging systems, few studies have, until recently, studied the impact of the merger process at large distances from the remnant. Up to a third of the pre-encounter material in the merger progenitors is tidally ejected during the interaction, into the tidal tails and bridges that form around the remnant (e.g. Toomre 1977; Barnes & Hernquist 1992b; Duc & Mirabel 1999; Combes 1999; Springel & White 1999; Hibbard et al. 2005). This collisional debris, especially that around gas-rich mergers, typically hosts star-forming regions, some of which may become progenitors of self-bound objects with masses typical of dwarf galaxies (e.g. Zwicky 1956; Schweizer 1978; Schombert et al. 1990; Mirabel et al. 1991, 1992; Hibbard et al. 2005). In contrast to normal

⋆ E-mail: s.kaviraj@imperial.ac.uk; skaviraj@astro.ox.ac.uk

dwarf galaxies, these 'tidal dwarfs' (TDs) are relatively metal-rich, with metallicities typical of the outer regions of spiral disks (e.g. Duc & Mirabel 1999; Duc et al. 2000; Weilbacher et al. 2000, 2003), free of (non-baryonic) dark matter, since their potential wells are too shallow to capture significant amounts of dark matter particles (e.g. Bournaud & Duc 2006; Duc et al. 2004, but see Gentile et al. 2007, Milgrom 2007) and may contribute a significant fraction of the nearby dwarf galaxy census (e.g. Kroupa 1997; Hunsberger et al. 1996; Okazaki & Taniguchi 2000; Metz & Kroupa 2007).

Two main mechanisms are postulated for TD formation. Jeans instabilities within the gas in the tidal tails can lead to gravitational collapse and the formation of self-bound objects (Elmegreen et al. 1993), akin to processes that produce giant molecular clouds. The Jeans masses are typically high - as the gas is heated by the merger - enabling the formation of relatively massive objects, some of which share the properties of local dwarf galaxies (e.g. Elmegreen et al. 1993; Struck et al. 2005; Bournaud & Duc 2006; Wetzstein et al. 2007; Smith et al. 2008). Alternatively, a large fraction of the stellar material in the progenitor disk may be ejected into the outer regions of the tidal tail, providing a local potential well into which gas condenses and fuels star formation (e.g. Barnes & Hernquist 1992b; Duc et al. 2004; Hancock et al. 2009). In the first scenario the stellar component is likely to be dominated by young stars, while in the second a substantial fraction of the stellar material is expected to be composed of old stars from the disks of the parent galaxies (see the recent review by Bournaud 2010). While a rich theoretical and observational literature has developed on the properties of nearby TDs (e.g. Wallin 1990; Schombert et al. 1990; Hibbard et al. 1994; Duc et al. 2000; Heithausen & Walter 2000; Braine et al. 2001; Hibbard et al. 2001; Temporin et al. 2003; Mundell et al. 2004; Neff et al. 2005; Hancock et al. 2007; Recchi et al. 2007; Bournaud et al. 2008; Werk et al. 2008; Boquien et al. 2009; Sheen et al. 2009; Koribalski & López-Sánchez 2009; Boquien et al. 2010; Wen et al. 2011), only relatively small samples of TDs have typically been exploited in any given study. A large statistical study of TDs at low redshift is clearly desirable.

An impediment to such a study is that a large, statistically meaningful sample of galaxy mergers in the local Universe has so far been lacking. This is because, given the small merger fraction at low redshift (a few percent, see e.g. Abraham et al. 1996; Conselice et al. 2003; Lavery et al. 2004; De Propris et al. 2005; Conselice et al. 2008; Darg et al. 2010a), a significant volume of the local Universe must be observed in order to extract an adequately large sample of merging systems. While the advent of modern surveys, such as the *Sloan Digital Sky Survey* (SDSS; York et al. 2000), has made such data available, the identification of mergers remains a challenge, both due to the prodigious size of these datasets and the technical difficulty in identifying peculiar systems like galaxy mergers.

Automated methods have often been employed to extract mergers from survey data but most have some limitations. Galaxy 'close pairs' - which are likely progenitors of mergers - can be identified in spectroscopic surveys (e.g. Patton et al. 2000; Le Fèvre et al. 2000; Nikolic et al. 2004; Ellison et al. 2008; Rogers et al. 2009). However, close-pair studies in the SDSS are likely to miss up to 80% of merging systems because fibre collisions prevent the SDSS from obtaining spectra for two objects that are within 55 arcseconds of each other in a single visit (see e.g. Darg et al. 2010a). Quantitative morphological parameters, e.g. Concentration, Asymmetry, Clumpiness, M_{20} and the Gini coefficient, have been extensively employed (often through the use of neural networks) to classify galaxy morphologies in large surveys (e.g. Abraham et al. 1996; Conselice et al. 2000; Abraham et al. 2003; Conselice et al. 2003; Ball et al. 2004; Lotz et al. 2004; Ferreras et al. 2005; Lahav et al. 1995; Lisker 2008; Andrae et al. 2011). However, it is difficult to define a parameter space that is *unique* to mergers and the results of such quantitative methods are typically checked and calibrated against visual inspection (e.g. Abraham et al. 1996; Ferreras et al. 2009; Jogee et al. 2009), which is arguably the most reliable method of morphological classification. The utility of visual inspection becomes particularly important for identifying peculiar systems, such as ongoing mergers and post-mergers (e.g. Cassata et al. 2005; Kaviraj 2010b). However, since it is prohibitively time-consuming for large datasets, visual inspection of the SDSS has, until the advent of the *Galaxy Zoo* (GZ) project, been limited to very small fractions (a few percent or less) of the full spectroscopic galaxy sample in this survey (Fukugita et al. 2007; Schawinski et al. 2007; Nair & Abraham 2010).

GZ is a citizen-science project which has used 250,000+ volunteers from the general public to morphologically classify the entire SDSS spectroscopic sample (∼1 million galaxies) through visual inspection of their optical images (Lintott et al. 2008, 2011). In particular, it offers an unprecedented route to extract a statistically meaningful sample of galaxy mergers in the local Universe. Darg et al. (2010a) have used the GZ database, based on the SDSS Data Release 6 (Adelman-McCarthy et al. 2008), to construct a robust sample of 3373 mergers with redshifts less than 0.1, typical mass ratios between 1:1 and 1:10 and a wide variety of separations, ranging from systems that are 'on approach' to ones that are almost fully coalesced. We refer readers to Darg et al. (2010a,b) for details of how this sample was constructed and the general properties of the galaxy mergers therein.

In this paper we exploit the Darg et al. merger sample to study the local TD population. The aim is to complement existing TD studies, which are typically based on relatively small samples of galaxy mergers, by offering a statistical view of the properties of the TD population in our local neighbourhood. The plan for this paper is as follows. In Section 2 we describe the compilation of a TD sample from the Darg et al. study. In Section 3 we study the general properties of TD-producing systems, cataloguing the morphologies, mass ratios and local environments of the parent mergers that produce TDs. In Section 4 we compare the properties of TDs (e.g. masses and colours) to their parents and explore the impact of Active Galactic Nuclei (AGN) in the parent galaxies on the formation of TDs in the tidal tails. In Section 5, we explore the star formation histories of the TDs. In particular, we investigate the ages and mass fractions of young stars in individual TDs, in order to compare the fraction of new stellar mass that is born in situ with that composed of old stars drawn from the parent disks. Finally,

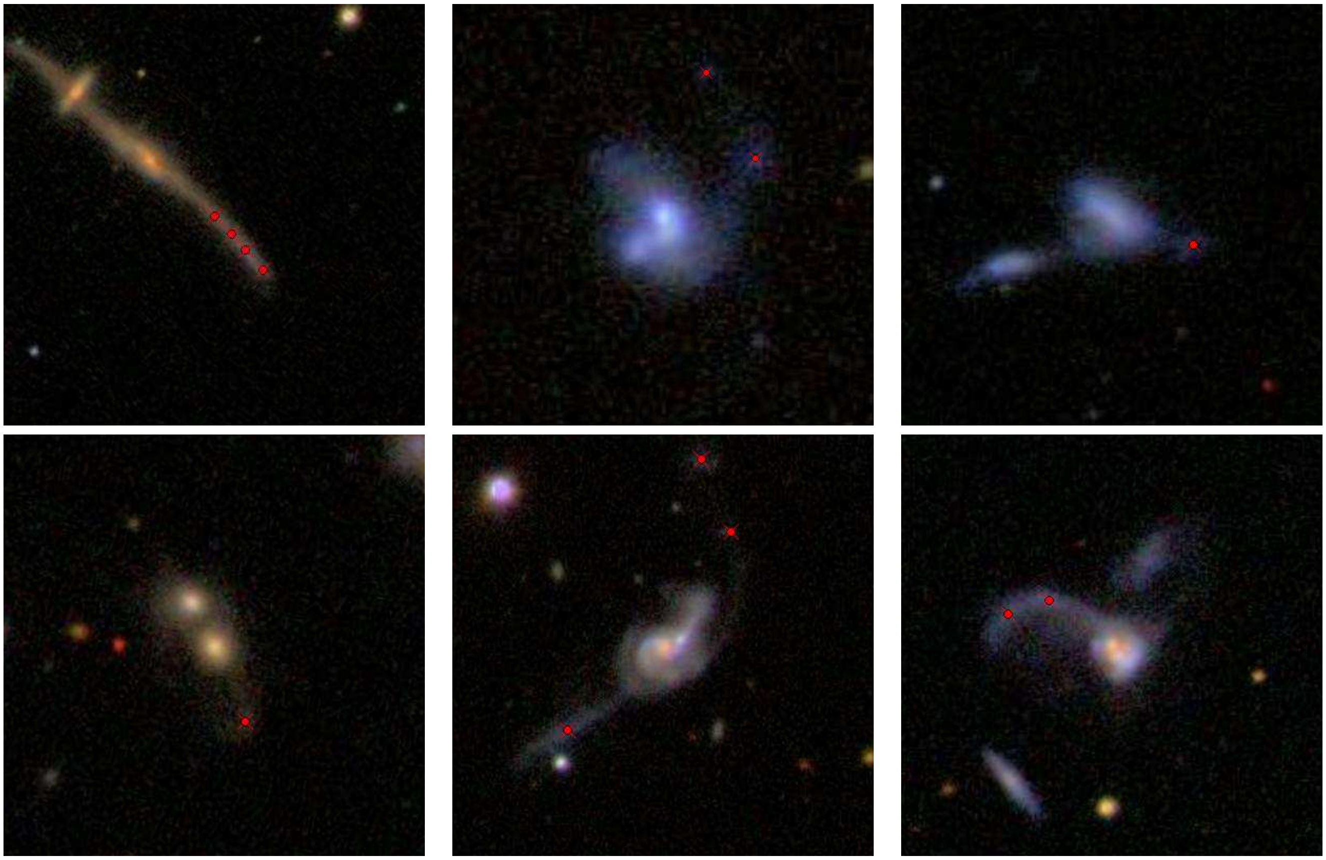

Figure 1. Examples of tidal dwarf candidates in the Galaxy Zoo mergers sample. Tidal dwarfs are selected as separate photometric objects, identified by the SDSS pipeline, that are clearly associated with the tidal debris around the merger in question. The positions of these objects are marked by the red crosses. This figure is available in colour in the online version of the journal.

in Section 6, we explore whether the TD population could make a significant contribution to the dwarf galaxy census in nearby clusters. We summarise our findings in Section 7.

2 COMPILING A SAMPLE OF TIDAL DWARFS

TDs are identified through visual inspection of the co-added g, r, i SDSS images of each merger. Separate photometric objects, extracted by the SDSS pipeline, that are clearly associated with the tidal debris in each merger are selected as TDs. In ∼20% of the cases there are multiple photometric objects associated with the same TD, with one object typically containing more than 90% of the flux. In such cases we sum the fluxes of all the photometric objects to estimate the flux of the TD in question. We note that if we simply used the brightest photometric object in each of these cases the general conclusions of our study would remain unaffected. This procedure yields 405 TDs. For each TD we also record an approximate position in relation to their parent galaxy - at the tidal-tail tips, within the tail or at the base of the tidal tail.

Figure 1 presents examples of TDs in our study. The position of the individual photometric objects, identified by the SDSS pipeline, that are selected as TDs are indicated on the images by red crosses. It should be noted that the identification of these objects relies on their association with the tidal debris in the parent mergers. However, since the objects are still 'attached' to their parents (which allows us to identify them as potential TDs in the first place), we cannot be certain whether they will evolve into independent self-bound objects and eventually contribute to the dwarf galaxy population. Hence the objects identified here are, strictly speaking, *TD candidates*.

The number of TDs per merger does not evolve across our redshift range ($0.01 < z < 0.1$), which suggests that the TD population identified at the lower end of our redshift range is similar to that identified at the upper end. In other words, we expect the TD population to be relatively homogeneous across the redshift range of this study. Since they are, by definition, associated with their parent merger, we calculate TD redshifts from the spectroscopic redshift information available for the parent galaxies. Due to fibre collisions the SDSS does not measure spectra for two objects that are within 55 arcseconds of each other in a single visit. Hence, in the overwhelming majority (80%) of systems in the Darg et al. sample, only one merger progenitor has a spectroscopic redshift. In these cases we take this as the redshift of all TDs associated with the merger. In cases where both progenitors have measured spectroscopic redshifts, we take their average as the redshift of the TDs belonging to that system. Since the two redshifts are very similar, this averaging procedure does not affect our results. The median redshift of the TDs studied in this paper is $z \sim 0.05$.

The redshifts are used to calculate absolute magnitudes for each TD, from the apparent magnitudes measured by the SDSS pipeline. K-corrections are computed using the latest version of the public `KCORRECT` code (Blanton et al. 2003a; Blanton & Roweis 2007). The absolute magnitudes are used to estimate stellar masses, using the calibrations of Bell et al. (2003). The error on these masses can be up to 0.3 dex. Figure 2 presents distributions of the basic properties (redshift, absolute r-band magnitude and stellar mass) of the TD sample in this paper. Median values are indicated using the dashed vertical lines. Note that, in the bottom panel (stellar mass), three additional vertical lines are shown, which indicate median values for TDs at the tips of tidal tails (red), within the tails (green) and at the base of tails (blue). We return to these TD subsets in Section 3.3 below.

3 PROPERTIES OF THE PARENT MERGERS

3.1 Parent morphologies and colours

We begin by cataloguing the properties of TD-producing mergers and compare them to the general merger population. 95% of binary mergers that produce TDs involve two spiral progenitors, while most remaining systems have at least one spiral progenitor. The fraction of TD-producing mergers where both parent galaxies have early-type morphology is less than 2% (at least in the sample studied here), strongly suggesting that TDs are unlikely to form in such mergers. It is instructive to check whether the significant lack of TDs in early-type - early-type (E-E) mergers is a real effect or whether they are not identified (partly) because the tidal tails in these mergers are too faint to be clearly detected in the standard SDSS imaging. By virtue of being a large-area survey, the standard SDSS imaging is relatively shallow, with only ∼54 second exposures in every filter (the r-band detection limit is ∼22 mag). To probe this issue further we explore the images of E-E mergers in this sample that lie in the SDSS Stripe 82 ($-50^\circ < \alpha < 59^\circ, -1.25^\circ < \delta < 1.25^\circ$) that offers 2 mag deeper imaging than the standard SDSS survey. The Stripe 82 has been imaged multiple times as part of the SDSS Supernova Survey (Frieman et al. 2008) and achieves limiting magnitudes of ∼ 24 mag in r-band, sometimes revealing faint tidal debris in mergers that may be invisible in the standard imaging (Kaviraj 2010a). Since it has an area of 270 deg^2, compared to the 9583 deg^2 area of the DR6 from which the Darg et al. sample is constructed, only 9 E-E mergers[1] in the Darg et al. study lie in this region of the sky. However, visual inspection of these images do not reveal any TDs not identified in the standard images, leaving our conclusions above unchanged.

Taking $(g - r) \sim 0.7$ as the transition between the blue cloud and the red sequence (see e.g. Strateva et al. 2001;

[1] The total number of mergers in the Darg et al. sample is 3373, with an E-E fraction of around 12%. The area of the Stripe 82 is 3% of the DR6 (270 deg^2/9583 deg^2). Thus we expect ($270 \times 3373 \times 0.12/9583 \sim 11$) E-E mergers in the Stripe 82. The actual number is 9 (consistent within counting errors).

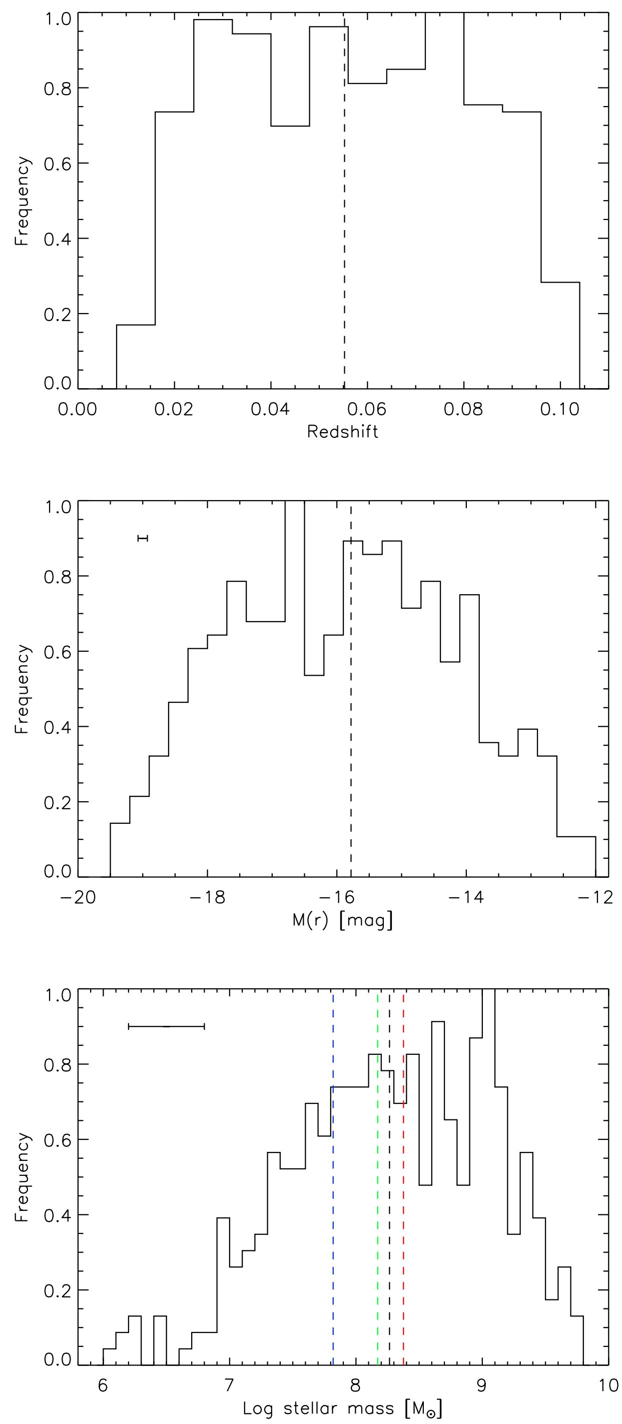

Figure 2. Distributions of redshift (top), r-band absolute magnitude (middle) and stellar mass (bottom) for the TD sample in this study. The stellar masses are calculated using the calibrations of Bell et al. (2003) and have errors of up to ∼0.3 dex. Median values of individual distributions are indicated using the vertical dashed lines. In the bottom panel (stellar masses) three additional vertical lines are shown which indicate median values for TDs at the tips of tidal tails (red), along the tails (green) and at the base of tails (blue). Errors in spectroscopic redshifts are negligible ($\sim 10^{-4}$). Magnitude errors are taken from the SDSS DR6 database. This figure is available in colour in the online version of the journal.

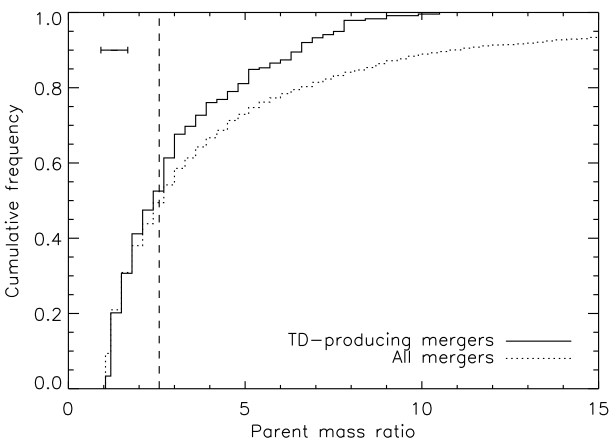

Figure 3. Parent mass ratios of TD-producing mergers (solid line) compared to the general merger population (dotted line). 95% of TD-producing mergers have mass ratios greater than ∼1:7. The median mass ratio of TD-producing mergers is ∼1:2.5 (shown using the vertical dashed line).

Blanton et al. 2003b), we find that in 85% of the parent mergers both progenitors are blue. In 12% at least one progenitor is blue, while in the remaining 3% of parent systems both progenitors are on the red sequence. Not unexpectedly TD formation becomes significantly more likely when both merger progenitors are gas-rich (and therefore in the blue cloud).

3.2 Parent mass ratios

Figure 3 indicates that 95% of TDs are produced by parent systems whose constituent galaxies have mass ratios greater than ∼1:7. The median parent mass ratio is ∼1:2.5. TDs are not produced by systems where the mass ratio exceeds ∼1:11. TD formation, in other words, appears much less likely in minor mergers (typically defined as systems with parent mass ratios less than 1:4). These observational results support recent theoretical work, which suggests that favourable conditions for TD formation require gas-rich mergers with mass ratios greater than 1:8 (Bournaud & Duc 2006).

3.3 Separation of tidal dwarfs from parent galaxies

In Figure 4 we show both the physical separation of TDs from their parents (left panel) and the separation normalised by the half-light radii ($R_{1/2}$) of the parent galaxies. 95% of TDs are within ∼20 kpc of their parent galaxies, corresponding to $\sim 15R_{1/2}$ (the median normalised separation is ∼17 kpc or $\sim 5R_{1/2}$), generally consistent with the theoretical simulations of Bournaud & Duc (2006).

As indicated in the bottom panel of Figure 2 above, TDs that lie further along the tidal tail appear to be more massive. The offset in the median masses (indicated by the dashed lines) of TDs born at the tips of the tidal tails compared to those born at the base of the tails is ∼0.6 dex (around a factor of 4). This mass offset is expected because the most massive objects are likely to form at the tail tips where the tidal debris accumulates (Elmegreen et al. 1993; Bournaud et al. 2004; Duc et al. 2004).

3.4 Local environment

We explore the local environment of TD-producing mergers by cross-matching with the SDSS environment catalogue of Yang et al. (2007, 2008), who use a halo-based group finder to separate the SDSS into 300,000+ structures, spanning rich clusters to the field. The catalogue provides estimates for the masses of the host dark matter haloes of individual SDSS galaxies, which are related to the traditional classifications of environment (field/group/cluster). Haloes with masses greater than $10^{14}M_\odot$ represent clusters, while those with masses in the range $10^{13}M_\odot$ to $10^{14}M_\odot$ represent groups. Smaller DM haloes represent the field. Figure 5 indicates that TD-producing mergers favour lower-density environments than the general merger population. ∼90% of TD-producing mergers reside in the field, with the remaining systems inhabiting groups. Almost none of the systems reside in clusters. This result is consistent with the fact that the availability of cold gas is a strong function of local environment. A cluster environment, in particular, is expected to be cold-gas-poor (e.g. Solanes et al. 2001) and therefore hostile to TD formation.

4 TIDAL DWARF VS. PARENT PROPERTIES: MASSES, COLOURS AND THE IMPACT OF AGN

We proceed by comparing how TD properties compare to those of their parent mergers. Figure 6 indicates that the stellar masses of 95% of TDs are less than 10% of the stellar mass of their parent mergers. The median TD-to-parent stellar mass ratio is around 0.6% (shown using the dashed line in Figure 6). Note that, since the masses are calculated from the photometric data, they correspond only to the stellar component of the galaxy. While the dynamical (total) masses of the TDs are expected to be similar to their stellar masses (since they do not contain significant amounts of dark matter), this is not the case for the parent spiral galaxies, which may contain 3-5 times as much dark as luminous matter (e.g. van Albada & Sancisi 1986; Ashman 1992; Salucci & Burkert 2000; Noordermeer et al. 2007; Salucci & Frigerio Martins 2009) inside ∼10 disk scalelengths (typically 20-40 kpc). The *total* TD-to-parent mass ratios are therefore likely to be several factors smaller than the stellar values derived here.

We now compare the TD colours to those of their parent galaxies. Recent studies have suggested that the presence of an AGN in a galaxy can affect the colours of objects in their immediate vicinity (Shabala et al. 2011), plausibly due to interaction between AGN-driven outflows and the gas reservoirs of these nearby galaxies. It is conceivable, therefore, that TD formation might also be affected by outflows due to nuclear activity in their parents. This may either suppress star formation by removing gas from the star-forming regions, as is typically envisaged in negative feedback scenarios (e.g. Silk & Rees 1998; Croton et al.

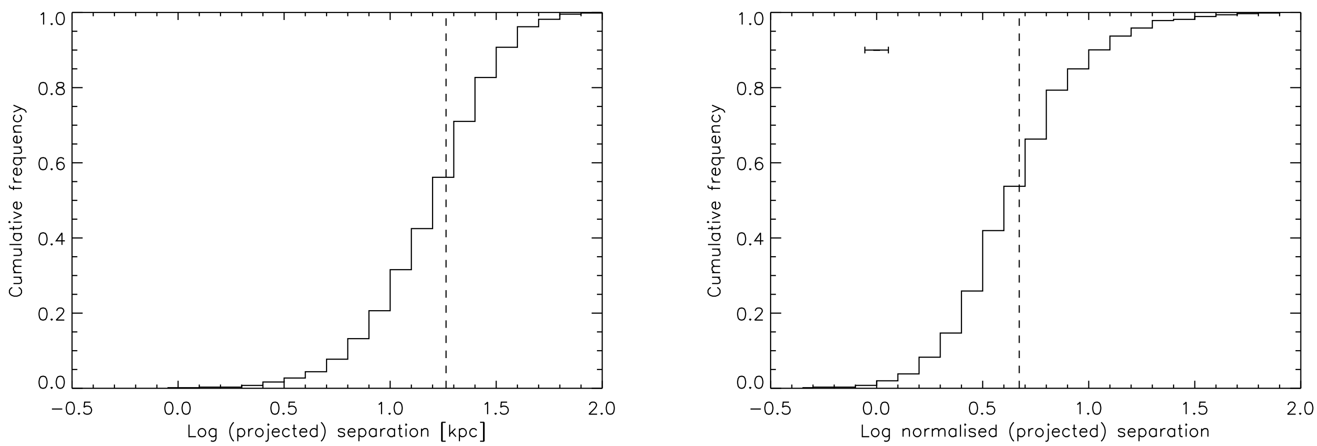

Figure 4. LEFT: Physical separation of TDs from their parent galaxies. **RIGHT:** Physical separation normalised by the half-light radius ($R_{1/2}$) of the parents. Median values are indicated using dashed vertical lines. The median separation is ~17 kpc and the median normalised separation is $\sim 4.5R_{1/2}$. 95% of TDs are within $\sim 15R_{1/2}$ of their parent galaxies. We assume that the uncertainties in RA and DEC values are negligible (hence no error bar is shown on the separations). The error in the normalised separation (right-hand panel) is driven by the error in the half-light radii of the parent galaxies.

2006; Tortora et al. 2009; Kaviraj et al. 2010) or alternatively enhance star formation through positive feedback by compressing cloud complexes (e.g. van Breugel et al. 1985; Mould et al. 2000; Silk 2005) in the tidal tails. Thus, we also wish to explore the colour difference between TDs and parents as a function of AGN activity in the parent galaxies.

Parent galaxies that host AGN are identified using a standard optical emission-line ratio analysis (e.g. Baldwin et al. 1981; Veilleux & Osterbrock 1987; Kauffmann et al. 2003; Kewley et al. 2006), which classifies objects as 'star-forming', 'composite' (which have signatures of both AGN and star formation), 'Seyfert', 'LINER' or 'quiescent'. The analysis is performed using the public `GANDALF` code (Sarzi et al. 2006)[2]. We assume that galaxies classified as composite, Seyfert or LINER host AGN.

Figure 7 shows that TDs are typically bluer than their parents. The median $(g-r)$ colour offset between TDs and parents is ~0.3 mag, similar to results of previous optical studies (e.g. Duc & Mirabel 1999) based on smaller TD samples. We also find that parents hosting AGN do not show a larger colour difference (within the errors) from their TDs than those without AGN. It seems unlikely, therefore, that feedback from AGN (either positive or negative) plays a role in TD evolution.

5 TIDAL DWARF STAR FORMATION HISTORIES

We investigate the star formation histories (SFHs) of TDs, in particular the relative fraction of stellar mass that is composed of new stars compared to the fraction that is constituted by old stars from the parent disks. We estimate the SFH of each TD by comparing colours constructed from the SDSS (u, g, r, i, z) magnitudes to a library of synthetic photometry that is based on model SFHs designed to approximate the stellar content of each TD.

Each model SFH is constructed using two instantaneous starbursts. The first burst, which characterises the old, underlying stellar population in the parent disks, is assumed to have an age of 7 Gyr, which represents an *average* age for the old disk stars. Recent studies that have decoupled the recent star formation from the old, underlying populations in star-forming spirals suggest average ages for the old stars around this value (see Kaviraj et al. 2009). We have checked that our conclusions remain unaffected if we change the age of the old stars to 10 Gyrs.

The second burst, which represents the young stellar content of the TDs, is allowed to vary in (i) age between 1 Myr and 7 Gyr and (ii) mass fraction between 0 and 1. We also include a range of values for the internal dust extinction, parametrised in terms of E_{B-V} from 0 to 1. The dust extinction is applied using the empirical law of Calzetti et al. (2000) to the SFH as a whole. We assume that the model SFHs have a metallicity of $0.3Z_{\odot}$, which is typical of the outer regions of spiral disks (e.g. Duc & Mirabel 1998; Weilbacher et al. 2000). The free parameters are, therefore, the age (t_2) and mass fraction (f_2) of the second burst and the dust content (E_{B-V}) of the TD. The model SFH library contains 1.5 million individual models. To build a library of synthetic photometry, each combination of free parameters is combined with the stellar models of Yi (2003) and convolved with the correct SDSS filtercurves. Since our TD sample spans a range in redshift ($0.01 < z < 0.1$), equivalent libraries are constructed at redshift intervals $\delta z = 0.005$.

For each TD in our sample, the free parameters are estimated by choosing the model library that is closest to it in redshift and comparing its (u, g, r, i, z) colours to every model in the synthetic library. In a Bayesian framework (see

[2] GANDALF simultaneously fits the emission and absorption lines and is designed to separate the relative contribution of the stellar continuum and of nebular emission in the spectra of nearby galaxies, while measuring the gas emission and kinematics. See http://star-www.herts.ac.uk/~sarzi/PaperV_nutshell/PaperV_nutshell.html for more details.

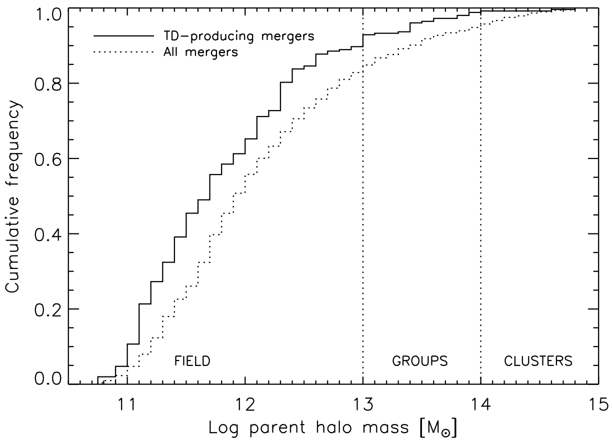

Figure 5. Local environments of TD-producing mergers (solid line) compared to the general merger populations (dotted line). TD-producing mergers typically inhabit field environments. Note that the Yang et al. (2007) catalogue, from which the environment measures are extracted, does not provide any error information on the host dark-matter halo masses.

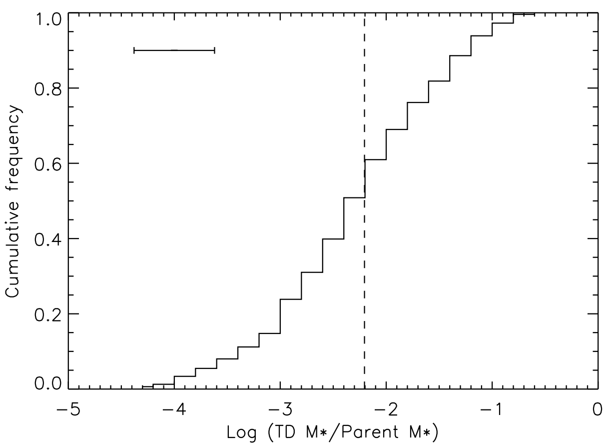

Figure 6. Ratio of TD stellar mass to parent stellar mass. 95% of TDs have stellar masses that are less than ~10% of the stellar masses of their parent galaxies. The median stellar mass ratio is ~0.6%, indicated by the dashed vertical line.

e.g. Sivia & Skilling 2006), for a vector $\mathbf{X}$ denoting parameters in the model and a vector $\mathbf{D}$ denoting the measured observables (in this case the colours),

$$\mathrm{prob}(\mathbf{X}|\mathbf{D}) \propto \mathrm{prob}(\mathbf{D}|\mathbf{X}) \times \mathrm{prob}(\mathbf{X}), \tag{1}$$

where $\mathrm{prob}(\mathbf{X}|\mathbf{D})$ is the probability of the model given the data (which is the quantity of interest), $\mathrm{prob}(\mathbf{D}|\mathbf{X})$ is the probability of the data given the model and $\mathrm{prob}(\mathbf{X})$ is the prior probability distribution of the model parameters. Since we assume a flat prior in all our model parameters above, $\mathrm{prob}(\mathbf{X})$ = constant so that

$$\mathrm{prob}(\mathbf{X}|\mathbf{D}) \propto \mathrm{prob}(\mathbf{D}|\mathbf{X}). \tag{2}$$

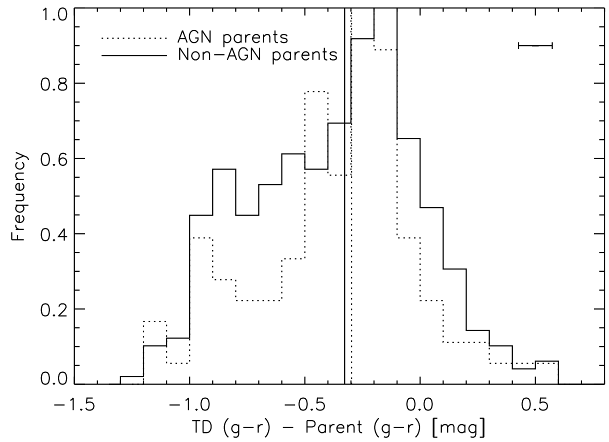

Figure 7. TD $(g-r)$ colour vs. parent $(g-r)$ colour. We show parents with and without AGN using the vertical lines. AGN are identified using an optical emission-line-ratio analysis (see text in Section 4 for details). Median values are indicated using vertical lines.

Assuming gaussian errors implies that

$$\mathrm{prob}(\mathbf{D}|\mathbf{X}) \propto \exp(-\chi^2/2), \tag{3}$$

where $\exp(-\chi^2/2)$ is the likelihood function, with χ^2 defined in the standard way, as the sum of the normalized residuals between the model-predicted observables M_i and the observed values D_i i.e.

$$\chi^2 = \sum_{i=1}^{N} \left(\frac{M_i - D_i}{\sigma_i} \right)^2 \tag{4}$$

The error that enters into the χ^2 equation (σ_i) is computed by adding, in quadrature, the observational uncertainties with the errors adopted for the stellar models, which we assume to be 0.05 mag in each optical filter (Yi 2003). $\mathrm{prob}(\mathbf{X}|D)$ is a *joint* probability distribution, dependent on all the model parameters. From this joint distribution, each free parameter is marginalised[3] to extract its one-dimensional probability distribution. We take the median value of this distribution as the best estimate of the parameter in question. The 25th and 75th quartile values (which encompass 50% of the probability) provide an estimate of the uncertainty in the parameter. This yields, for every TD, a best estimate and error for each free parameter. It is worth noting that the derived error represents the combined uncertainty in the parameter estimate due to the observational and model errors and the various degeneracies between the free parameters.

Figure 8 presents the distribution of free parameters for our TD population. Not unexpectedly, and in agreement with the wider literature, we find that a substantial young stellar component exists in the TDs, with ages less than

[3] To isolate the effect of a single parameter X1 in, for example, a two-parameter model $[\mathrm{prob}(X|D) \equiv \mathrm{prob}(X1, X2|D)]$ we can integrate out the effect of X2 to obtain the marginalized probability distribution for X1: $\mathrm{prob}(X_1|D) = \int_0^\infty \mathrm{prob}(X_1, X_2|D) dX_2$.

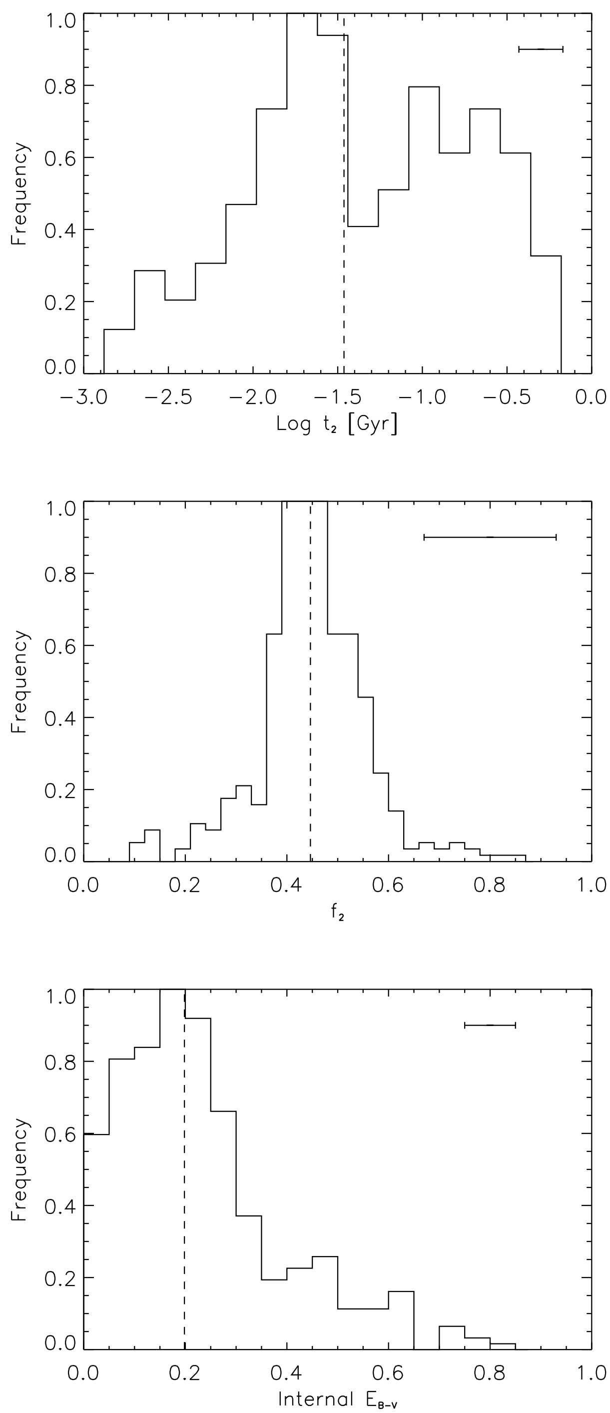

Figure 8. Estimated values of the free parameters that drive the TD star formation histories: age (t_2; top) and mass fraction (f_2; middle) of the young stars and internal extinction in the galaxy (E_{B-V}; bottom). Median values of the distributions are shown using the dashed lines. While a substantial young stellar component exists in TDs, with ages less than ∼0.5 Gyr (the median age is ∼30 Myr), an equally significant component, drawn from old stars in the parent disks, also appears to be present in these systems.

∼0.5 Gyr (the median derived age is ∼30 Myr). The derived mass fractions in young stars largely range between 20 and 80% with a median value of ∼45%. The estimated internal extinctions are typically lower than $E_{B-V} \sim 0.5$ ($A_V \lesssim 1.5$), with a median value of ∼0.2. These results indicate that a significant fraction (around half) of the stellar content of TDs is likely to be composed of old stars from the parent disks. While the mass-fraction uncertainties are large (around ±15%), *the bulk of the TDs are inconsistent with a purely young stellar population.* It is likely, therefore, that TDs are not formed purely through gas condensations in the tidal tails but that their potential wells contain significant contributions from pre-existing stellar material from the parent disks.

6 COULD THE DWARF GALAXY CENSUS HAVE A SIGNIFICANT CONTRIBUTION FROM TIDAL DWARFS?

We conclude our analysis by investigating the potential contribution of TDs to the dwarf galaxy population observed in the Universe today. The analysis in Section 3 indicates that TDs typically form in gas-rich or wet major mergers that involve two spiral galaxies. If the number of wet major mergers experienced by a massive galaxy over a Hubble time is N_{wet}, the average number of TDs produced per wet major merger is N_{TD} and the fraction of TDs that survive for a Hubble time is S, then the number of TDs expected per massive galaxy today is estimated to be

$$N_{wet} \times N_{TD} \times S. \qquad (5)$$

Integration of the empirical major merger rate in massive galaxies over time indicates that every massive galaxy typically experiences ∼ 4 major mergers over a Hubble time (Conselice 2007, see also Bell et al. 2006, Lotz et al. 2006). Typically, at most one of these major mergers takes place after $z \sim 1$ (e.g. Conselice et al. 2003; Lin et al. 2004; Bell et al. 2006; Jogee et al. 2009). Since the merger activity at $z > 1$ is likely to be dominated by interactions between two gas-rich spiral galaxies (e.g. Khochfar & Burkert 2003; Kaviraj et al. 2009), this suggests that 3 out of 4 of the major mergers experienced by a typical massive galaxy are likely to be wet.

Theoretical work suggests that ∼50% of TDs with *masses greater than* 10^8 $M_\odot$ are likely to survive for a Hubble time (Bournaud 2010). *TD-producing* mergers each create, on average, 1.2 TDs in this mass range. However, only ∼18% of major gas-rich mergers produce such TDs in the first place. Hence, the average number of TDs with masses greater than 10^8 M$_\odot$ per gas-rich major merger is ∼0.22 (i.e. 1.2×0.18). Therefore the number of such TDs per massive galaxy today is estimated to be $3 \times 0.22 \times 0.5 = 0.33$.

The *observed* galaxy mass function indicates that dwarf galaxies are the dominant galaxy type in the local Universe (e.g. Sandage et al. 1985; van den Bergh 1992; Sabatini et al. 2003). The ratio of dwarf to massive galaxies (D/M) in Coma (Secker & Harris 1996), restricted to dwarfs with masses greater than $\sim 10^8$ M$_\odot$ ($M(r) < -14.5$), is ∼5.8. The corresponding value in Virgo is very similar (Ferguson & Sandage 1991). If the TD contribution to this ratio is ∼0.33 (as calculated above) then ∼6% of the dwarf population in clusters could plausibly have a tidal origin.

It should be noted that this estimate assumes that the TD production rate in high-redshift mergers is similar to that in their nearby counterparts. Mergers at high redshift typically involve higher gas masses (e.g. Daddi et al. 2010; Tacconi et al. 2010) and may yield more TDs than their local counterparts (e.g. Wetzstein et al. 2007). However, simulations of high-redshift major mergers (Bournaud et al. 2011), in which the interstellar medium is more clumpy and turbulent than in their nearby counterparts (e.g. Elmegreen et al. 2009), suggest that these interactions do not produce the long tidal tails seen in local mergers. This may have implications for the lifetime of tidal objects, since they are formed closer to their parent galaxies, making them more vulnerable to disruption. Definitive studies of the TD production rate at high redshift requires both further simulation work and empirical studies of high-redshift mergers at the peak epoch of stellar mass assembly ($2 < z < 4$, see e.g. Madau et al. 1998; Hopkins 2004; Hopkins & Beacom 2006) using high-resolution data e.g. from the Wide Field Camera 3 (WFC3) or the Extremely Large Telescopes (ELTs). Nevertheless, it is worth noting that even if TD production rates were several factors higher in the early Universe, it remains unlikely that the *entire* local dwarf galaxy census has a tidal origin.

7 SUMMARY

We have performed a statistical observational study of the TD population in the local Universe, by exploiting a large, homogeneous sample of galaxy mergers compiled from the SDSS DR6 using the Galaxy Zoo project. The aim of this work has been to explore the statistical properties of local TDs, both to complement existing observational studies (which are typically based on relatively small samples of mergers) and as a comparison to the wide body of theoretical work that has recently been performed on the formation and evolution of TDs.

Our results indicate that 95% of TD-producing mergers involve interactions between two spiral galaxies, both typically residing in the blue cloud. The overwhelming majority of these parent systems have mass ratios greater than ∼1:7, reside in field environments and are located within 15 optical half-light radii of the parent galaxies. TD stellar masses are less than 10% of the stellar masses of their parents, with those forming at the tips of tidal tails typically a factor of 4 more massive than those that form at the base of the tails. TDs are typically bluer than their parents, the median colour offset being ∼0.3 mag in $(g - r)$. The presence of an AGN in the parent galaxies does not affect the TD colours. It is worth noting that only around a fifth of gas-rich major mergers produce massive TDs (with masses greater than 10^8 $M_\odot$).

An analysis of their star formation histories indicates that TDs contain both newly formed stars and old stellar material drawn from the disk of their parent galaxies. The young stellar components have ages less than ∼0.5 Gyr, with a median derived age of ∼30 Myr in the TD population as a whole. The young components contribute stellar mass fractions between 20 and 80%, with a typical value of ∼45%. The estimated internal extinctions are typically lower than $E_{B-V} \sim 0.5$ ($A_V \lesssim 1.5$). The derived mass fractions of young stars strongly suggest that TD formation is not simply the result of gas condensations along tidal tails in mergers. Stellar material from the parent disks contributes almost equally to the mass in these objects.

Finally, we have explored the likely TD contribution to the dwarf galaxy census in the nearby Universe. By combining the number of gas-rich major mergers experienced by a massive galaxy over a Hubble time with the average number of TDs expected to form in each merger and their expected survival rate, we have estimated the number of dwarfs per massive galaxy that are likely to come from the TD population. Comparison to the observed ratio of dwarf to massive galaxies in nearby clusters suggests that ∼6% of the dwarfs in local clusters may be of tidal origin, assuming that the TD production rate in the nearby Universe is representative of that in high-redshift mergers. Observational studies of TDs in high-redshift mergers, using forthcoming data from the WFC3 and the ELTs, are keenly anticipated to further explore the role of mergers in the formation of the dwarf galaxy population at the present day.

ACKNOWLEDGEMENTS

The anonymous referee is thanked for several constructive comments on the manuscript. SK acknowledges fellowships from the Royal Commission for the Exhibition of 1851, Imperial College London, Worcester College, Oxford and support from the BIPAC institute at Oxford. This publication has been made possible by the participation of more than 250,000 volunteers in the Galaxy Zoo project. Their contributions are individually acknowledged at http://www.galaxyzoo.org/Volunteers.aspx. Support for the work of KS was provided by NASA through Einstein Postdoctoral Fellowship grant numbers PF9-00069, issued by the Chandra X-ray Observatory Center, which is operated by the Smithsonian Astrophysical Observatory for and on behalf of NASA under contract NAS8-03060.

Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the U.S. Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS Web Site is http://www.sdss.org/.

The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions. The Participating Institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, University of Basel, University of Cambridge, Case Western Reserve University, University of Chicago, Drexel University, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Scientist Group, the Chinese Academy of Sciences (LAMOST), Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, Ohio State University, University of Pittsburgh, University of Portsmouth, Princeton

University, the United States Naval Observatory, and the University of Washington.

REFERENCES

Abraham R. G., Tanvir N. R., Santiago B. X., Ellis R. S., Glazebrook K., van den Bergh S., 1996, MNRAS, 279, L47

Abraham R. G., van den Bergh S., Nair P., 2003, ApJ, 588, 218

Adelman-McCarthy J. K., et al. 2008, ApJS, 175, 297

Andrae R., Jahnke K., Melchior P., 2011, MNRAS, 411, 385

Ashman K. M., 1992, PASP, 104, 1109

Baldwin J. A., Phillips M. M., Terlevich R., 1981, PASP, 93, 5

Ball N. M., Loveday J., Fukugita M., Nakamura O., Okamura S., Brinkmann J., Brunner R. J., 2004, MNRAS, 348, 1038

Barnes J. E., Hernquist L., 1992a, ARAA, 30, 705

Barnes J. E., Hernquist L., 1992b, Nature, 360, 715

Bell E. F., McIntosh D. H., Katz N., Weinberg M. D., 2003, ApJS, 149, 289

Bell E. F., Naab T., McIntosh D. H., et al. 2006, ApJ, 640, 241

Blanton M. R., et al. 2003a, AJ, 125, 2348

Blanton M. R., et al. 2003b, ApJ, 594, 186

Blanton M. R., Roweis S., 2007, AJ, 133, 734

Boquien M., Duc P., Galliano F., Braine J., Lisenfeld U., Charmandaris V., Appleton P. N., 2010, AJ, 140, 2124

Boquien M., Duc P., Wu Y., Charmandaris V., Lisenfeld U., Braine J., Brinks E., Iglesias-Páramo J., Xu C. K., 2009, AJ, 137, 4561

Bournaud F., et al. 2011, ApJ, 730, 4

Bournaud F., 2010, Advances in Astronomy, 2010

Bournaud F., Bois M., Emsellem E., Duc P., 2008, Astronomische Nachrichten, 329, 1025

Bournaud F., Duc P., 2006, A&A, 456, 481

Bournaud F., Duc P.-A., Amram P., Combes F., Gach J.-L., 2004, A&A, 425, 813

Braine J., Duc P., Lisenfeld U., Charmandaris V., Vallejo O., Leon S., Brinks E., 2001, A&A, 378, 51

Calzetti D., Armus L., Bohlin R. C., Kinney A. L., Koornneef J., Storchi-Bergmann T., 2000, ApJ, 533, 682

Cassata P., Cimatti A., Franceschini A., et al. 2005, MNRAS, 357, 903

Combes F., 1999, in J. E. Barnes & D. B. Sanders ed., Galaxy Interactions at Low and High Redshift Vol. 186 of IAU Symposium, Extended Gas in Interacting Systems. pp 89–+

Conselice C. J., 2007, in Combes F., Palous J., eds, IAU Symposium Vol. 235 of IAU Symposium. pp 381–384

Conselice C. J., Bershady M. A., Dickinson M., Papovich C., 2003, AJ, 126, 1183

Conselice C. J., Bershady M. A., Jangren A., 2000, ApJ, 529, 886

Conselice C. J., Rajgor S., Myers R., 2008, MNRAS, 386, 909

Croton D. J., et al. 2006, MNRAS, 365, 11

Daddi E., et al. 2010, ApJ, 713, 686

Darg D. W., et al. 2010a, MNRAS, 401, 1043

Darg D. W., et al. 2010b, MNRAS, 401, 1552

De Propris R., Liske J., Driver S. P., Allen P. D., Cross N. J. G., 2005, AJ, 130, 1516

Duc P., Bournaud F., Masset F., 2004, A&A, 427, 803

Duc P., Brinks E., Springel V., Pichardo B., Weilbacher P., Mirabel I. F., 2000, AJ, 120, 1238

Duc P., Mirabel I. F., 1999, in J. E. Barnes & D. B. Sanders ed., Galaxy Interactions at Low and High Redshift Vol. 186 of IAU Symposium, Tidal Dwarf Galaxies. pp 61–+

Duc P.-A., Mirabel I. F., 1998, A&A, 333, 813

Ellison S. L., Patton D. R., Simard L., McConnachie A. W., 2008, AJ, 135, 1877

Elmegreen B. G., Elmegreen D. M., Fernandez M. X., Lemonias J. J., 2009, ApJ, 692, 12

Elmegreen B. G., Kaufman M., Thomasson M., 1993, ApJ, 412, 90

Ferguson H. C., Sandage A., 1991, AJ, 101, 765

Ferreras I., Lisker T., Carollo C. M., Lilly S. J., Mobasher B., 2005, ApJ, 635, 243

Ferreras I., Lisker T., Pasquali A., Kaviraj S., 2009, MNRAS, 395, 554

Frieman J. A., et al. 2008, AJ, 135, 338

Fukugita M., et al. 2007, AJ, 134, 579

Gentile G., Famaey B., Combes F., Kroupa P., Zhao H. S., Tiret O., 2007, A&A, 472, L25

Hancock M., Smith B. J., Struck C., Giroux M. L., Appleton P. N., Charmandaris V., Reach W. T., 2007, AJ, 133, 676

Hancock M., Smith B. J., Struck C., Giroux M. L., Hurlock S., 2009, AJ, 137, 4643

Heithausen A., Walter F., 2000, A&A, 361, 500

Hibbard J. E., et al. 2005, ApJL, 619, L87

Hibbard J. E., Guhathakurta P., van Gorkom J. H., Schweizer F., 1994, AJ, 107, 67

Hibbard J. E., van der Hulst J. M., Barnes J. E., Rich R. M., 2001, AJ, 122, 2969

Hopkins A. M., 2004, ApJ, 615, 209

Hopkins A. M., Beacom J. F., 2006, ApJ, 651, 142

Hunsberger S. D., Charlton J. C., Zaritsky D., 1996, ApJ, 462, 50

Jogee S., et al. 2009, ApJ, 697, 1971

Kauffmann G., Heckman T. M., White S. D. M., et al. 2003, MNRAS, 346, 1055

Kaviraj S., 2010a, MNRAS, 406, 382

Kaviraj S., 2010b, MNRAS, 408, 170

Kaviraj S., Peirani S., Khochfar S., Silk J., Kay S., 2009, MNRAS, 394, 1713

Kaviraj S., Schawinski K., Silk J., Shabala S. S., 2010, arXiv:1008.1583

Kewley L. J., Groves B., Kauffmann G., Heckman T., 2006, MNRAS, 372, 961

Khochfar S., Burkert A., 2003, ApJ, 597, L117

Koribalski B. S., López-Sánchez Á. R., 2009, MNRAS, 400, 1749

Kroupa P., 1997, New Astronomy, 2, 139

Lahav O., et al. 1995, Science, 267, 859

Lavery R. J., Remijan A., Charmandaris V., Hayes R. D., Ring A. A., 2004, ApJ, 612, 679

Le Fèvre O., Abraham R., Lilly S. J., et al. 2000, MNRAS, 311, 565

Lin L., Koo D. C., Willmer C. N. A., et al. 2004, ApJ, 617, L9

Lintott C., et al. 2011, MNRAS, 410, 166
Lintott C. J., et al. 2008, MNRAS, 389, 1179
Lisker T., 2008, ApJS, 179, 319
Lotz J. M., Madau P., Giavalisco M., Primack J., Ferguson H. C., 2006, ApJ, 636, 592
Lotz J. M., Primack J., Madau P., 2004, AJ, 128, 163
Madau P., Pozzetti L., Dickinson M., 1998, ApJ, 498, 106
Metz M., Kroupa P., 2007, MNRAS, 376, 387
Milgrom M., 2007, ApJL, 667, L45
Mirabel I. F., Dottori H., Lutz D., 1992, A&A, 256, L19
Mirabel I. F., Lutz D., Maza J., 1991, A&A, 243, 367
Mould J. R., et al. 2000, ApJ, 536, 266
Mundell C. G., James P. A., Loiseau N., Schinnerer E., Forbes D. A., 2004, ApJ, 614, 648
Nair P. B., Abraham R. G., 2010, ApJS, 186, 427
Neff S. G., et al. 2005, ApJL, 619, L91
Nikolic B., Cullen H., Alexander P., 2004, MNRAS, 355, 874
Noordermeer E., van der Hulst J. M., Sancisi R., Swaters R. S., van Albada T. S., 2007, MNRAS, 376, 1513
Okazaki T., Taniguchi Y., 2000, ApJ, 543, 149
Patton D. R., Carlberg R. G., Marzke R. O., Pritchet C. J., da Costa L. N., Pellegrini P. S., 2000, ApJ, 536, 153
Recchi S., Theis C., Kroupa P., Hensler G., 2007, A&A, 470, L5
Rogers B., Ferreras I., Kaviraj S., Pasquali A., Sarzi M., 2009, MNRAS, 399, 2172
Sabatini S., Davies J., Scaramella R., Smith R., Baes M., Linder S. M., Roberts S., Testa V., 2003, MNRAS, 341, 981
Salucci P., Burkert A., 2000, ApJL, 537, L9
Salucci P., Frigerio Martins C., 2009, in E. Pécontal, T. Buchert, P. di Stefano, & Y. Copin ed., EAS Publications Series Vol. 36 of EAS Publications Series, The mass distribution in Spiral galaxies. pp 133–140
Sandage A., Binggeli B., Tammann G. A., 1985, AJ, 90, 1759
Sarzi M., Falcón-Barroso J., Davies R. L., et al. 2006, MNRAS, 366, 1151
Schawinski K., Kaviraj S., Khochfar S., et al. 2007, ApJS, 173, 512
Schombert J. M., Wallin J. F., Struck-Marcell C., 1990, AJ, 99, 497
Schweizer F., 1978, in E. M. Berkhuijsen & R. Wielebinski ed., Structure and Properties of Nearby Galaxies Vol. 77 of IAU Symposium, Galaxies with long tails. pp 279–284
Secker J., Harris W. E., 1996, ApJ, 469, 623
Shabala S. S., Kaviraj S., Silk J., 2011, MNRAS, pp 336–+
Sheen Y., et al. 2009, AJ, 138, 1911
Silk J., 2005, MNRAS, 364, 1337
Silk J., Rees M. J., 1998, A&A, 331, L1
Sivia D. S., Skilling J., 2006, Data Analysis–A Bayesian Tutorial, 2nd edn. Oxford Science Publications
Smith B. J., Struck C., Hancock M., Giroux M. L., Appleton P. N., Charmandaris V., Reach W., Hurlock S., Hwang J., 2008, AJ, 135, 2406
Solanes J. M., Manrique A., García-Gómez C., González-Casado G., Giovanelli R., Haynes M. P., 2001, ApJ, 548, 97
Springel V., Di Matteo T., Hernquist L., 2005, MNRAS, 361, 776
Springel V., White S. D. M., 1999, MNRAS, 307, 162
Steinmetz M., Navarro J. F., 2002, Nature, 7, 155
Strateva I., et al. 2001, AJ, 122, 1861
Struck C., Kaufman M., Brinks E., Thomasson M., Elmegreen B. G., Elmegreen D. M., 2005, MNRAS, 364, 69
Tacconi L. J., et al. 2010, Nature, 463, 781
Temporin S., Weinberger R., Galaz G., Kerber F., 2003, ApJ, 587, 660
Toomre A., 1977, in Tinsley B. M., Larson R. B., eds, Evolution of Galaxies and Stellar Populations pp 401–+
Tortora C., Antonuccio-Delogu V., Kaviraj S., Silk J., Romeo A. D., Becciani U., 2009, MNRAS, 396, 61
van Albada T. S., Sancisi R., 1986, Royal Society of London Philosophical Transactions Series A, 320, 447
van Breugel W., Filippenko A. V., Heckman T., Miley G., 1985, ApJ, 293, 83
van den Bergh S., 1992, A&A, 264, 75
Veilleux S., Osterbrock D. E., 1987, ApJS, 63, 295
Wallin J. F., 1990, AJ, 100, 1477
Weilbacher P. M., Duc P., Fritze-v. Alvensleben U., 2003, A&A, 397, 545
Weilbacher P. M., Duc P., Fritze v. Alvensleben U., Martin P., Fricke K. J., 2000, A&A, 358, 819
Wen Z., Zheng X., Zhao Y., Gao Y., 2011, ArXiv e-prints
Werk J. K., Putman M. E., Meurer G. R., Oey M. S., Ryan-Weber E. V., Kennicutt Jr. R. C., Freeman K. C., 2008, ApJ, 678, 888
Wetzstein M., Naab T., Burkert A., 2007, MNRAS, 375, 805
Yang X., Mo H. J., van den Bosch F. C., 2008, ApJ, 676, 248
Yang X., Mo H. J., van den Bosch F. C., Pasquali A., Li C., Barden M., 2007, ApJ, 671, 153
Yi S. K., 2003, ApJ, 582, 202
York D. G., et al. 2000, AJ, 120, 1579
Zwicky F., 1956, Ergebnisse der exakten Naturwissenschaften, 29, 344