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The standard Λ cold dark matter model of galaxy formation postulates a hierarchical growth of structure over cosmic time (e.g. White 1978; Somerville & Primack 1999; Cole et al. 2000; Hatton et al. 2003). In this paradigm, galaxies and their host dark-matter haloes grow, both through mergers with systems of similar mass ('major mergers'), and via the accretion of smaller objects ('minor mergers'). A natural consequence of the shape of the observed luminosity function – in which smaller galaxies far outnumber their more massive counterparts (e.g. Blanton et al. 2001; Cole et al. 2001) – is that minor mergers are significantly more common than major interactions.

While past studies of merging have largely explored the effects of major mergers (e.g. Toomre & Toomre 1972; Hernquist 1989; Barnes & Hernquist 1992; Jesseit et al. 2007; Darg et al. 2010a, b), a growing literature is highlighting the important role of minor mergers (mass ratios $\lesssim$1:4) in influencing massive-galaxy evolution. Minor merging is a frequent process, that is both predicted (e.g.

Maller et al. 2006; Fakhouri & Ma 2008; Stewart et al. 2008; Kaviraj et al. 2009) and observed (e.g. Lin et al. 2004; Jogee et al. 2009; López-Sanjuan et al. 2010) to be at least ∼3–4 times more common than major interactions at late epochs. While each individual minor interaction may have a relatively small effect on the massive galaxy, it is becoming increasingly clear that the *cumulative* impact of minor mergers over cosmic time is significant, both in terms of the stellar content of massive galaxies and their structural properties.

The role of this process in fuelling star formation in massive galaxies has recently been explored via ultraviolet (UV) studies of early-type galaxies (ETGs). Survey-scale UV data, from *GALEX* at $z \sim 0$ (e.g. Yi et al. 2005; Kaviraj et al. 2007) and deep optical surveys at intermediate redshift (e.g. Kaviraj et al. 2008), have revealed widespread star formation in ETGs at late epochs. A strong correlation is observed between the presence of morphological disturbances and blue UV colours in nearby ETGs (Kaviraj et al. 2011; see also Schweizer et al. 1990; Schweizer & Seitzer 1992), indicating that the star formation is driven by mergers, and not by processes like stellar mass loss or accretion that would leave the stellar morphology of the system undisturbed (Kaviraj et al. 2011, see also Crockett et al. 2011). However, the major-merger rate at late epochs ($z < 1$) cannot satisfy the number of disturbed ETGs,

suggesting that *minor* mergers dominate the star formation in these objects (Kaviraj et al. 2011, see also Shabala et al. 2012). Note that these studies primarily sample low-density environments, making these results relevant largely to ETGs that inhabit groups and the field (and not dense clusters). However, since clusters are typically hostile to star formation (e.g. Dressler 1984; Moore et al. 1999; Kimm, Yi & Khochfar 2011), the bulk of the ETG star formation budget is expected to reside in low-density environments.

While past empirical work on minor-merger-driven star formation has focused on ETGs, this process will clearly affect massive galaxies regardless of morphology. Kaviraj (2014, hereafter K14) has leveraged the ETG studies mentioned above to derive a lower limit for the fraction of star formation in spiral galaxies that is also likely triggered by minor mergers. The K14 results indicate that *at least* a quarter of the star formation budget in local spirals is attributable to this process, yielding a lower limit for the minor-merger-driven fraction of *cosmic* star formation of $\sim$35 per cent. The observed correlation between black hole and galaxy stellar mass (e.g. Gültekin et al. 2009) further implies that a similar fraction of black hole growth may also be induced by this process.

The work on minor-merger-driven star formation is mirrored by studies of the size evolution of massive galaxies over cosmic time. Recent empirical work has demonstrated that the effective radii of massive galaxies increase, on average, by factors of 3–5 over the lifetime of the Universe (e.g. Daddi et al. 2005; Trujillo et al. 2006; Buitrago et al. 2008; van Dokkum et al. 2008; Saracco, Longhetti & Andreon 2009; Cimatti, Nipoti & Cassata 2012; Newman et al. 2012; Ryan et al. 2012; Huertas-Company et al. 2013). While secular mechanisms, such as adiabatic expansion driven by stellar mass loss or strong AGN feedback, have been proposed to explain this evolution (e.g. Fan et al. 2008; Damjanov et al. 2009, but see Trujillo, Ferreras & de La Rosa 2011; Bluck et al. 2012), consensus favours size evolution via mergers, with the bulk of the increase attributed to minor mergers over cosmic time (e.g. Khochfar & Silk 2006; Bournaud, Jog & Combes 2007; Naab, Johansson & Ostriker 2009; Nipoti et al. 2009; Oser et al. 2012).

While it is increasingly well established that the minor-merger process can significantly influence the star formation and structural properties of massive galaxies, its overall impact on cosmic star formation and black hole growth remains poorly understood. Since spirals dominate the star formation budget at late epochs (K14), this translates into a need to understand, in detail, the impact of minor mergers on the spiral population across cosmic time. While K14 has derived a lower limit ($\sim$25 per cent) for the fraction of star formation in spirals that is triggered by this process at the present day, an estimate of its global impact on galaxy evolution demands a more accurate measurement of this fraction, beyond the lower limit derived by K14.

A burgeoning literature has now begun probing the impact of minor mergers on spiral galaxies. Empirical studies of spiral minor-merger *remnants* have largely focused on individual case studies of very nearby galaxies. These efforts typically demonstrate enhancements in star formation and, in some cases, nuclear activity (see e.g. Smith et al. 1996; Knapen et al. 2004; Mazzuca et al. 2006; Saintonge et al. 2012), indicating that the minor-merger process is indeed influencing the growth of both the galaxy and its central black hole. Studies of minor galaxy *pairs* – i.e. systems where the two objects have not coalesced – also show enhancements, especially when the system is close to coalescence (e.g. separations <10 kpc), although the effect is much weaker than in major mergers (Ellison et al. 2008; Li et al. 2008; Robaina et al. 2009; Scudder et al. 2012; Patton et al. 2013). The triggering of star formation in the massive progenitor of

a minor merger is expected to peak at the 'remnant' stage, during the coalescence of the satellite, when the tidal forces on the disc are highest (see e.g. Mihos & Hernquist 1994; Kaviraj et al. 2009) - statistical studies of minor-merger *remnants* are, therefore, very desirable for gaining insights into this process.

In a similar vein, while past theoretical efforts have largely explored the impact of *major* mergers, recent work has begun to study the role of minor interactions in spiral galaxies. In qualitative agreement with the empirical case studies mentioned above, theoretical efforts do find star formation enhancement in minor-merger remnants. The enhancement typically anticorrelates with the system mass ratio (e.g. Hernquist 1989; Mihos & Hernquist 1994; Hernquist & Mihos 1995; Cox et al. 2008), but the actual increase in star formation efficiency depends critically on the specific theoretical prescriptions utilized in individual simulations.

Since the enhancement of star formation occurs at the 'remnant' stage of the process, i.e. when the smaller companion is coalescing with the primary, an *empirical* survey-scale study of spiral minor-merger remnants becomes a compelling exercise. In this paper, we present such a study, whose principal aims are to (1) quantify the enhancement of star formation due to minor mergers in spiral galaxies, (2) estimate the fraction of total star formation in spirals, and in massive galaxies in general, that is triggered by minor mergers and (3) quantify the enhancement of black hole growth in spirals due to the minor-merger process. This study significantly extends the K14 analysis (which derived a robust lower limit for point 2 above), with the overall objective of gauging the global impact of minor mergers on the evolution of the spiral galaxy population.

This paper is organized as follows. In Section 2, we describe the galaxy sample that underpins this study and the selection of minor-merger remnants via visual inspection. In Sections 3 and 4, we explore the enhancement of star formation in spirals due to minor mergers and use these results to estimate the fractions of the spiral and cosmic star formation budgets that are triggered by the minor-merger process. In Section 5, we explore minor-merger-driven enhancement of nuclear accretion in spiral galaxies. We summarize our findings in Section 6. Throughout this study, we use the *WMAP3* cosmological parameters (Komatsu et al. 2011): $\Omega_m = 0.241$, $\Omega_\Lambda = 0.759$, $h = 0.732$, $\sigma_8 = 0.761$.

2 DATA

2.1 Galaxy sample

The galaxies used in this study are based on a sample that was recently compiled by K14. The objects are drawn from the Sloan Digital Sky Survey (SDSS) Stripe 82, an $\sim$300 deg^2 region along the celestial equator in the Southern Galactic Cap ($-50° < \alpha < 59°$, $-1°.25 < \delta < 1°.25$) (Frieman et al. 2008) that offers a co-addition of 122 imaging runs (York et al. 2000; Abazajian et al. 2009), yielding images that are $\sim$2 mag deeper than the standard-depth, 54 s SDSS scans (which have magnitude limits of 22.2, 22.2 and 21.3 mag in the g, r and i bands, respectively).

K14 classified their galaxies into standard morphological classes (E/S0, Sa, Sb, Sc, Sd, see Hubble 1926; de Vaucouleurs 1959), using visual inspection of both the standard-depth, colour images from the SDSS DR7 and their deeper r-band Stripe 82 counterparts. While morphological parameters, such as concentration, asymmetry, clumpiness, M_{20} and the Gini coefficient, have often been employed for morphological classification of survey data sets (e.g. Conselice et al. 2003; Lotz, Primack & Madau 2004), they are calibrated against results from visual inspection (e.g. Abraham et al. 1996),

which yields better precision in the classification of galaxy morphologies. Leveraging the findings of recent work that has employed visual inspection of SDSS galaxies (see e.g. Kaviraj et al. 2007; Fukugita et al. 2007; Schawinski et al. 2007; Lintott et al. 2008, 2011; Nair & Abraham 2010), K14 restricted their sample to $r < 16.8$ and $z < 0.07$, where morphological classification from SDSS images is likely to be most reliable. The final K14 compilation contains ∼6500 galaxies in this redshift and magnitude range.

In our analysis below, we employ published stellar masses (Kauffmann et al. 2003) and star formation rates (SFRs; Brinchmann et al. 2004) from the latest version of the publicly available MPA-JHU value-added SDSS catalogue.[1] Briefly, stellar masses are calculated by comparing *ugriz* photometry of individual galaxies to a large grid of synthetic star formation histories, based on the Bruzual & Charlot (2003) stellar models. Model likelihoods are calculated from the values of χ^2, and 1D probability distributions for free parameters, such as stellar masses, are constructed via marginalization. The median of this 1D distribution is taken to be the best estimate for the parameter in question, with the 16th and 84th percentile values (which enclose 68 per cent of the total probability) yielding a '1σ' uncertainty.

The SFRs are estimated via two different methods, depending on the ionization class of the galaxy, that is derived using an optical emission-line ratio analysis (Kewley et al. 2006, see also Baldwin, Phillips & Terlevich 1981; Veilleux & Osterbrock et al. 1987; Kauffmann et al. 2003), using the values of [N ii]/Hα and [O iii]/Hβ measured from the SDSS spectra of individual galaxies (Brinchmann et al. 2004; Tremonti et al. 2004). Objects in which all four emission lines are detected with a signal-to-noise ratio greater than 3 are classified as either 'star-forming', 'composite' (i.e. hosting both star formation and AGN activity), 'Seyfert' or 'LINER', depending on their location in the [N ii]/Hα versus [O iii]/Hβ diagram (see e.g. Kewley et al. 2006). Galaxies without any detection in all four lines are classified as 'quiescent'.

SFRs for galaxies classified as 'star-forming' (i.e. where the nuclear ionization is driven by star formation) are estimated by comparing galaxy spectra to a library of models from Charlot & Longhetti (2001), with a dust treatment that follows the empirical model of Charlot & Fall (2000). For galaxies that are classified as 'quiescent', or those that are classified as 'AGN/Composite' (in which a significant fraction of the nuclear emission is likely driven by a central AGN), SFRs are calculated using the D4000 break.[2] The correlation between specific SFR and D4000 break for the 'star-forming' subsample is used to estimate the specific SFR of the galaxy in question. Note that the SFRs used here are corrected for both internal extinction and the fixed size of the SDSS fibre. We refer readers to Brinchmann et al. (2004) for full details of the modelling.

2.2 Selection of minor-merger remnants

Theoretical work indicates that the strong gravitational torques induced by major mergers (mass ratios $\gtrsim 1\!:\!4$) destroy rotationally

supported discs and produce pressure-supported spheroidal systems (e.g. Toomre & Toomre 1972; Toomre 1977; Hernquist 1989; Barnes & Hernquist 1992; Cox et al. 2006; Naab, Jesseit & Burkert 2006; Jesseit et al. 2007; Hopkins et al. 2008). While major interactions involving very high gas fractions may yield late-type remnants that rebuild discs from the remnant gas (e.g. Springel, Di Matteo & Hernquist 2005; Robertson et al. 2006; Hopkins et al. 2009), such conditions are rare at low redshift (Kannappan 2004). Thus, systems in the local Universe that exhibit both disc morphology and tidal disturbances are likely to be remnants of minor mergers, since a major interaction would have destroyed the disc and created a spheroid.

While disturbed spirals are likely minor-merger remnants, visual identification of such systems requires deep, high-resolution colour imaging. Deep images are required for detecting the tidal features that result from recent minor interactions (e.g. Kaviraj 2010), while high-resolution, colour images enable us to efficiently differentiate discs, which have inhomogeneous structure, from the smooth, homogeneous light distributions of early-type (i.e. spheroidal) galaxies. The combination of standard-depth colour images and co-added scans makes the SDSS Stripe 82 an ideal platform for a large-scale study of spiral minor-merger remnants. To identify our sample, we visually inspect both the standard-depth colour image and the *r*-band Stripe 82 counterpart of each K14 galaxy and flag those that are morphologically disturbed.

Fig. 1 shows examples of disturbed spirals and, for comparison, their counterparts in the ETG population. The morphological disturbances are most easily detected in the Stripe 82 imaging, making these deep images indispensable for this exercise. Fig. 2 shows examples of relaxed spirals and ETGs that do not show evidence for disturbed morphologies in the SDSS images. Note that, while previous work has flagged morphological disturbances via visual inspection (e.g. Nair & Abraham 2010), these have been based on standard-depth SDSS images. Since the faint tidal debris produced by minor mergers (e.g. Peirani et al. 2010) is only visible in deeper imaging, such as that available in the Stripe 82 (Kaviraj 2010), using just the standard-depth images would significantly underestimate the fraction of galaxies that have undergone recent minor interactions.

3 MINOR-MERGER-DRIVEN STAR FORMATION IN SPIRAL GALAXIES

3.1 Enhancement of star formation due to minor mergers

We begin by setting up a theoretical framework to quantify the fraction of star formation in spiral galaxies that is triggered by the minor-merger process.

We define the following quantities: ϕ_0 is the normal specific star formation rate (SSFR) of a spiral galaxy in the absence of a minor merger, m is its stellar mass, D is the duty cycle of the remnant phase of the minor-merger process, i.e. the fraction of time the galaxy appears disturbed due to minor mergers and η is the enhancement in the SSFR while the galaxy is in this disturbed phase. The stellar mass (S) produced in a time period (δt) can then be expressed as

$$S = \underbrace{\phi_0 (1 - D) m \delta t}_{S_{\mathrm{NORM}}} + \underbrace{\eta \phi_0 D m \delta t}_{S_{\mathrm{MM}}}, \tag{1}$$

where S_{NORM} represents the stellar mass formed while the galaxy is in a normal star-forming mode (i.e. in the absence of a minor merger), while S_{MM} represents the stellar mass formed while the galaxy experiences enhanced star formation during the remnant

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[2] The D4000 break is produced by the absorption of short-wavelength photons from metals in stellar atmospheres. The feature is stronger in systems that are deficient in hot, blue stars (e.g. Poggianti & Barbaro 1997), making it a good estimator of SFR in systems with weak emission lines, or those in which the relevant diagnostic lines, such as Hα, are contaminated by non-thermal sources (e.g. AGN).
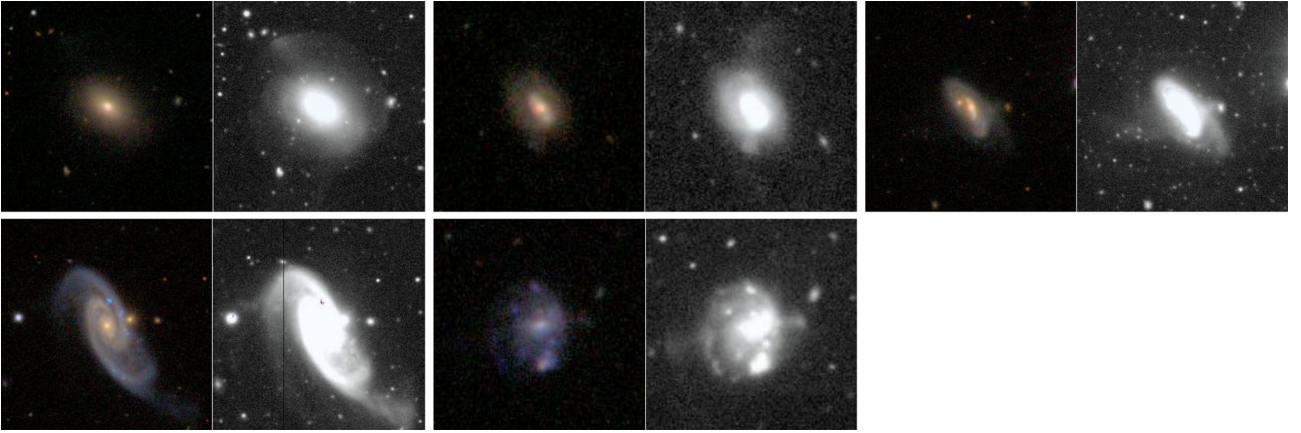
Figure 1. Examples of standard-depth, multicolour images (left) and their deeper *r*-band Stripe 82 counterparts (right) of spiral minor-merger remnants. We show examples of early-type (row 1, left), Sa (row 1, middle), Sb (row 1, right), Sc (row 2, left) and Sd (row 2, middle) galaxies. The morphological disturbances are typically clearer in the Stripe 82 imaging, making these deeper images necessary for this exercise. While ETGs are not considered in this study, we show an example of a disturbed ETG for comparison to the spirals. Note that the images may look better on screen than in print.
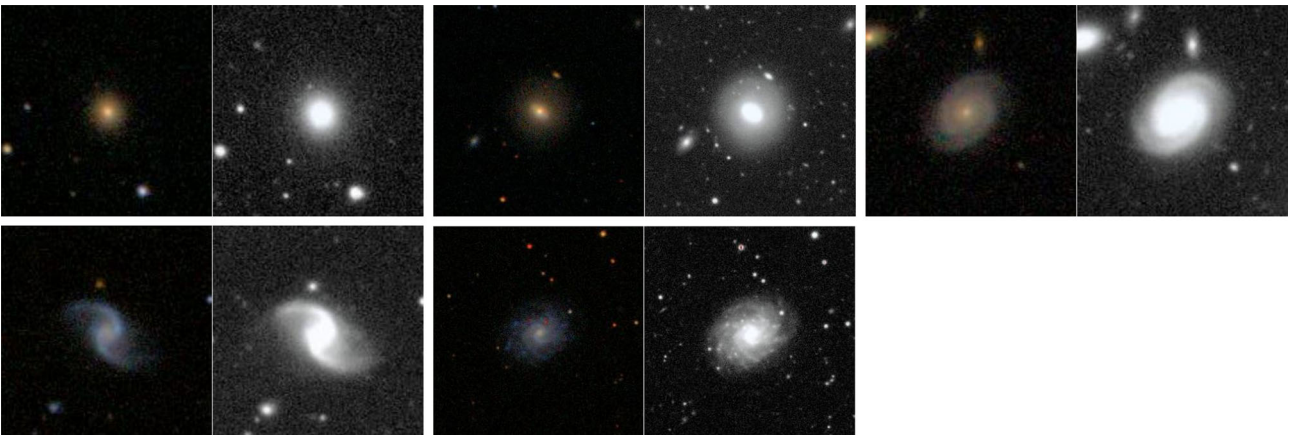

Figure 2. Examples of standard-depth, multicolour (left) images and their deeper *r*-band Stripe 82 counterparts (right) of relaxed spiral galaxies. Note the lack of tidal disturbances compared to the objects shown in Fig. 1 above. We show examples of early-type (row 1, left), Sa (row 1, middle), Sb (row 1, right), Sc (row 2, left) and Sd (row 2, middle) galaxies. While ETGs are not considered in this study, we show an example of an ETG for comparison to the spirals. Note that the images may look better on screen than in print.

phase of a minor merger. The fraction of star formation triggered by minor mergers (F_{MM}) is then:

$$F_{MM} = \frac{S_{MM}}{S} = \frac{\eta D}{1 + D(\eta - 1)}. \quad (2)$$

As might be expected, F_{MM} depends on a combination of the enhancement of star formation during the disturbed phase and the fraction of time that the galaxy spends in this phase. While we cannot measure these quantities for individual galaxies, we can calculate *mean* statistical estimates for η and D, if large populations of minor-merger remnants are available, as is the case in this study. As K14 has suggested, the star formation enhancement is likely to be higher in 'later' morphological types, which host larger gas reservoirs (e.g. Kannappan 2004) and smaller bulges that are less able to stabilize the disc against gas inflows (e.g. Mihos & Hernquist 1994; Hernquist & Mihos 1995; Martig et al. 2009). It is, therefore, desirable to perform this analysis as a function of morphological type.

Assuming that the detectability of morphological disturbances does not evolve in the short redshift range studied here, the duty cycle (*D*) is given by the fraction of galaxies that are disturbed.

In column 2 of Table 1, we present the fraction of disturbed spirals as a function of morphology. We find similar duty cycles (~11–17 per cent) across different morphological types. The values for Sa and Sb systems is similar to that found in the massive ETG population (18 per cent; see Kaviraj 2010). The decreasing duty cycles towards 'later' morphological types is likely driven by the average galaxy mass being lower in these classes, which affects the ability of the galaxy to attract satellites.

We calculate mean SSFR enhancements (η) using the published MPA-Garching SSFRs of the relaxed and disturbed spirals in each morphological class. To perform this comparison statistically, we extract, in each morphological class (Sa/Sb/Sc, etc.), 1000 random samples of relaxed galaxies, each with the same redshift and *r*-band distribution as that of the disturbed systems (the samples are not necessarily independent). Matching in redshift and magnitude implies that we are comparing galaxies at similar distances and with similar luminosities, making the comparison more meaningful. We then calculate the median SSFR of each 'matched' relaxed sample and construct the ratio (disturbed:relaxed) of median SSFRs for each comparison, which we define as the SSFR enhancement. This yields, for each morphological class, a distribution of 1000 SSFR

Table 1. Columns from left to right: (1) Morphological class, (2) duty cycle (*D* in equation 1) of the remnant phase of the minor-merger process, i.e. the fraction of time the galaxy appears disturbed due to minor mergers, (3) enhancement of SSFR in remnant phase of the minor-merger process (η in equation 1), (4) the fraction of star formation driven by minor mergers, calculated using equation (1), (5) proportion of the star formation budget in spiral galaxies that is hosted by this morphological class (from K14). Note that the star formation budgets calculated by K14 include corrections for Malmquist bias, via the standard $1/V_{max}$ weighting method.

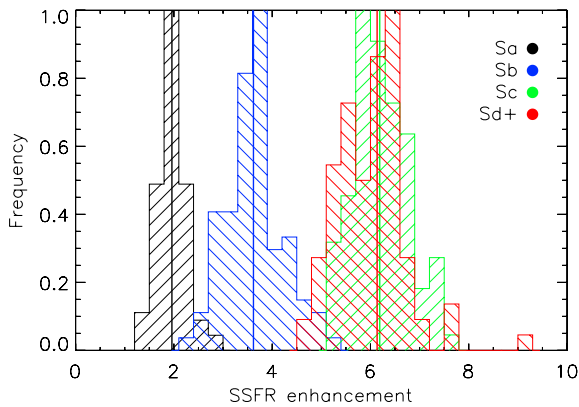| Morphology	*D*	η	F_{mm} (via equation 2)	Proportion of spiral SF budget (from K14)
Sa	0.16	1.98	0.27	0.19
Sb	0.17	3.62	0.43	0.34
Sc	0.13	6.15	0.48	0.32
Sd/Irr	0.11	6.14	0.43	0.15

Figure 3. The SSFR enhancement in disturbed spirals in different morphological classes: S0 (far left), Sa (second from left), Sc (histogram on the right, with hatching from bottom left to top right), Sd and later (histogram on the right, with hatching from bottom right to top left). The enhancement is defined as the ratio of the median SSFR of the disturbed objects to that in a control (undisturbed) sample that has the same redshift and *r*-band distribution. See text in Section 3.1 for details.

enhancements (Fig. 3). We take the median of this distribution as a typical value for η for the morphological class in question.

Fig. 3 indicates that the SSFR is enhanced in minor-merger remnants regardless of galaxy morphology, the enhancement increasing in galaxies that have 'later' morphological type. While disturbed Sa galaxies exhibit median enhancements of around a factor of ∼2, this climbs to a factor of ∼6 for Sc galaxies and later morphological classes. The values of η are presented in column 3 of Table 1.

3.2 The fraction of disc and cosmic star formation that is triggered by minor mergers

Given the values of η and *D* calculated above, we use equation (2) to estimate the fraction of star formation that is triggered by minor mergers (F_{MM}) in each morphological class (column 4 in Table 1). The values of F_{MM} are ∼0.27 for Sa galaxies and climb to ∼0.43–0.48 in Sb and later morphological types. Multiplying the values of F_{MM} with the proportion of the star formation budget in spirals that is hosted by each morphological class (column 5 in table 1, taken from K14), then yields an estimate for the *total* fraction of star formation in spiral galaxies that is attributable to minor mergers. We estimate this fraction to be ∼40 per cent (consistent with the results of K14, who estimated an empirical lower limit for this value of ∼25 per cent.) Thus, a significant fraction of stellar mass in local spirals is likely to be created in enhanced star formation episodes during the latter stages of minor mergers.

We note that our analysis has only considered systems that are visibly morphologically disturbed, and not those that may have experienced a recent minor merger, but where the mass ratio is not sufficiently high to induce morphological disturbances at the depth of the SDSS images. While we assume that the star formation enhancement in such mergers is negligible, the robustness of this assumption is difficult to test without dedicated theoretical simulations, which are beyond the scope of this paper.

In addition, given the evidence for star formation enhancement in minor galaxy *pairs* described above, an (additional) contribution to minor-merger-driven star formation is expected while the galaxies are at small separations but still 'on approach'. However, given a duty cycle of ∼2 per cent and typical enhancement of a factor of ∼3 (Scudder et al. 2012), the extra contribution of this phase is around a per cent and therefore does not alter our overall conclusions. Nevertheless, as a result of both these points, the value of 40 per cent derived above may indeed also be a lower limit.

Finally, it is worth combining our results with the star formation in ETGs, which is driven by minor mergers (at least in low-density environments) and accounts for ∼14 per cent of the cosmic star formation budget (K14). This indicates that *around half (0.4 × 0.86 per cent [LTGs] + 14 per cent [ETGs]) of the cosmic star formation activity at the present day is triggered by the minor-merger process.*

4 MINOR-MERGER-TRIGGERED NUCLEAR ACCRETION IN SPIRALS

The observed correlation between galaxy stellar mass and the mass of the central black hole (e.g. Gültekin et al. 2009; McConnell et al. 2011) suggests that the black hole and its host galaxy co-evolve (e.g. Di Matteo et al. 2008). While the correlation is strongest in early-type systems (e.g. Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000; Rix et al. 2004), it also exists in spirals, albeit with larger intrinsic scatter (Gültekin et al. 2009). Thus, for every unit of stellar mass that is built, a certain fraction is, *on average*, accreted on to the black hole (in early-type systems this fraction is ∼1/1000, see e.g. Merritt & Ferrarese 2001).

The positive correlation between stellar and black hole mass in spirals suggests that the enhanced star formation in the disturbed spirals should be accompanied by enhanced nuclear accretion. It is worth noting, however, that the larger intrinsic scatter in the relation for spirals indicates a higher level of stochasticity in the feeding of their central black holes, so that nuclear accretion may not be as tightly coupled to star formation as in ETGs. Nevertheless, it is interesting to explore whether nuclear activity is enhanced in the disturbed spirals, implying enhanced growth of their central black holes.

Recent work suggests that, at least in major mergers, AGN activity (and therefore the nuclear accretion rate) peaks in the post-merger, i.e. remnant phase (Carpineti et al. 2012). It seems reasonable to assume that the same holds true for minor mergers, since star formation is preferentially fuelled in the remnant phase. Hence, the enhancement of nuclear accretion during the minor-merger process is also best explored in the remnant phase, i.e. via the disturbed spirals, as has been done for the star formation analysis above.

Following the recent literature (e.g. Kewley et al. 2006; Schawinski et al. 2007), we estimate the nuclear accretion rate by exploiting the luminosity of the forbidden [O III] line at 5007 Å. This exercise is complicated by the fact that this line has contributions from both the central AGN and star formation. We therefore use the emission-line analysis described in Section 2.1 to restrict our study to Seyferts, where the ionization is dominated by the central AGN. We do not consider LINERs, as the ionization in these systems may have several sources, including shocks or evolved stellar populations (such as P-AGB stars) associated with recent star formation (e.g. Ho, Filippenko & Sargent 1993; Sarzi et al. 2010). Following Kewley et al. (2006), we calculate a quantity that is proportional to the specific accretion rate, by dividing the O[III] luminosity by σ^4, where σ is the stellar velocity dispersion. While the O[III] luminosity scales with the AGN's bolometric luminosity (Heckman et al. 2004), σ^4 provides an estimate of the mass of the central black hole (e.g. Ferrarese & Merritt 2000; Gebhardt et al. 2000).

Restricting our study to Seyferts significantly reduces the number of objects in the analysis. As a result, it is not possible to explore the specific accretion rate as a function of fine morphological classes (e.g. Sa/Sb/Sc, etc.) as was the case in the star formation analysis above. Instead, we split the spiral galaxies into early spirals (Sa systems) and late spirals (Sb and 'later' types). Table 2 indicates how the relaxed and disturbed spirals split according to these ionization classes. The disturbed spirals typically exhibit higher fractions of objects classified as 'star-forming', 'composite' and 'Seyfert', regardless of morphology.

In Fig. 4, we present the distribution of specific accretion rates for these two populations (which lie in a similar range of values to that found in recent studies of massive galaxies, e.g. Schawinski et al. 2007). We find that nuclear accretion is indeed enhanced in the minor-merger remnants, indicating that the minor-merger process also enhances black hole growth (KS tests on the accretion-rate distributions of relaxed and disturbed galaxies result in probabilities of 92 and 98 per cent, that they are different in the early spirals and late spirals, respectively). Mirroring the results of the star formation analysis, the enhancement is larger in the later morphological types. While the median enhancement is relatively mild ($\sim$40 per cent) in early spirals, it rises to a factor of $\sim$2 in the late spirals.
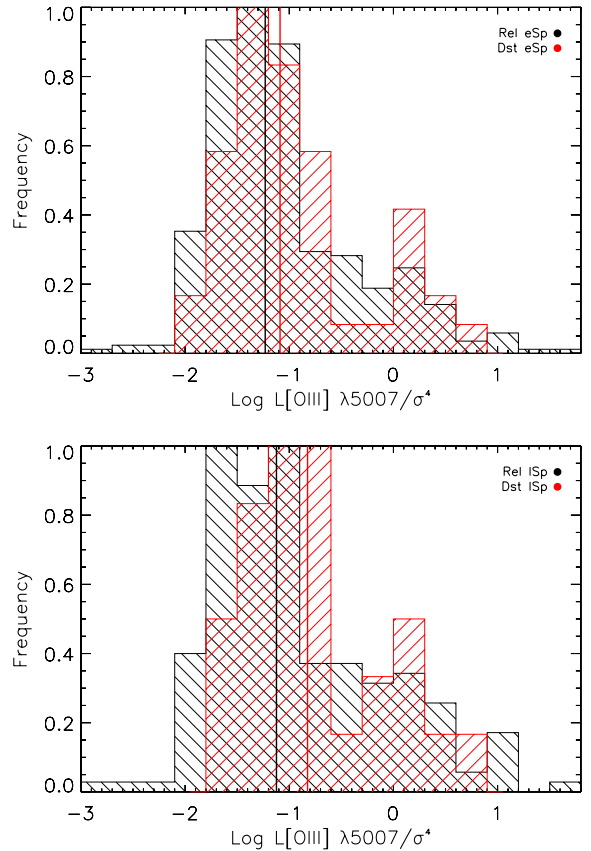

Figure 4. Enhancement in the specific nuclear accretion rate for early (Sa) spirals (top) and late (Sb and later) spirals (bottom). Note the log scale on the horizontal axis. The median enhancement is relatively small ($\sim$40 per cent) in the early spirals, rising to a factor of $\sim$2 in the late spirals.

It is worth noting, however, that the median enhancement in nuclear accretion appears significantly less pronounced than that in star formation activity, regardless of morphological class. Unless nuclear accretion peaks at a different point during the minor-merger process to star formation (which seems unlikely given the arguments above), this suggests a weaker coupling between the minor-merger-driven growth of stellar and black hole mass in spiral galaxies (see also Shankar et al. 2012). Given that a significant fraction of stellar mass is likely triggered by the minor-merger process, this weaker coupling between star formation and nuclear accretion may be partly responsible for the larger intrinsic scatter in the stellar versus black hole mass correlation in spirals.

Table 2. Number fractions in different emission-line classes for relaxed and disturbed objects, split by early and late spirals (see Section 4). See Section 2.1 for a description of how galaxies are classified into these ionization classes (QS = quiescent, SF = star forming, Low S/N SF = low signal-to-noise star-forming, CP = composite, Sy = Seyfert, LI = LINER). The first three rows correspond to the early spiral population, while the next three rows correspond to the late spiral population. f(Dst)/f(Rel) indicates the ratio (disturbed:relaxed) for each ionization class.

	QS	SF	Low S/N SF	CP	Sy	LI
Relaxed early spirals	0.10	0.39	0.20	0.12	0.08	0.11
Disturbed early spirals	0.07	0.47	0.13	0.15	0.10	0.08
f(Dst)/f(Rel)	0.70	1.21	0.65	1.25	1.25	0.73
Relaxed late spirals	0.04	0.57	0.22	0.07	0.04	0.06
Disturbed late spirals	0.04	0.62	0.13	0.10	0.06	0.05
f(Dst)/f(Rel)	1.00	1.09	0.59	1.43	1.50	0.83

5 SUMMARY

We have used a sample of bright ($r < 16.8$), local ($z < 0.07$) galaxies from the SDSS Stripe 82 to probe the role of minor mergers in driving stellar mass and black hole growth in nearby massive spiral (disc) galaxies. Our study has been based on a sample of galaxies from K14, that have been visually classified into standard morphological classes (E/S0, Sa, Sb, Sc, Sd, etc.) using both colour images from the SDSS DR7 and their deeper r-band counterparts from the Stripe 82.

Since 'major' (i.e. equal or nearly equal-mass) mergers produce spheroids, an effective route to studying spiral galaxies that are minor-merger remnants is to use spirals that are morphologically disturbed. The disturbed morphology indicates a recent interaction, and the continued presence of a disc indicates that the interaction was not a major merger (since this would have destroyed the disc and created a spheroid). Using the DR7 and Stripe 82 images, we have flagged spiral galaxies in the K14 sample that are morphologically disturbed, thus selecting the nearby spiral minor-merger remnant population in the SDSS Stripe 82 field.

We have used this sample to quantify the stellar mass growth in spiral galaxies that is plausibly triggered by minor mergers. As indicated by equation (2) and described in Section 3.1, the proportion of minor-merger-driven star formation depends both on the enhancement of star formation during the remnant phase of a minor merger (η) and the fraction of time galaxies spend in this enhanced star formation mode (the 'duty cycle', D). While we cannot measure these quantities for individual galaxies, we can calculate mean statistical estimates for η and D, if large populations of minor-merger remnants are available, as is the case in this study.

Assuming that the detectability of morphological disturbances does not evolve in the short redshift range studied here, D can be estimated by the fraction of galaxies that are morphologically disturbed. η can be calculated using the ratio of the measured SSFRs in the relaxed spirals to that in the disturbed spirals.

The duty cycle is relatively insensitive to morphological class and ranges between 11 and 17 per cent. The SSFRs are enhanced in the disturbed spirals, regardless of morphology, with the enhancement increasing in galaxies that have 'later' morphological type. While disturbed Sa galaxies exhibit SSFR enhancements of a factor of ∼2, this increases to a factor of ∼6 for Sc and later morphological types. Our results indicate that the star formation enhancements are higher in galaxies that host larger internal gas reservoirs and smaller bulges (that are less able to stabilize the disc against radial gas inflows), as might be expected from the recent literature.

The duty cycles and SSFR enhancements imply that the fraction of star formation driven by minor mergers range from ∼27 per cent in Sa galaxies to ∼43–48 per cent in Sb and later morphological types. Combining this with the proportion of the star formation budget hosted by each morphological class then yields *a total minor-merger-driven fraction of star formation in spirals of ∼40 per cent*. This is consistent with the results of K14, who estimated an empirical lower limit for this value of ∼25 per cent. Thus, while most of the star formation in today's spiral galaxies is unrelated to mergers, a significant fraction is attributable to the minor-merger process. It is worth noting that our analysis has been restricted to galaxies that show morphological disturbances. Thus, we have disregarded systems that might have undergone a recent minor merger, but where the mass ratio is not high to induce morphological disturbances at the depth of the Stripe 82 imaging. We have also disregarded the contribution of the phase when minor galaxy pairs are close to coalescence but still on approach (although we have shown that

this contribution is relatively insignificant). Nevertheless, both these points imply that the estimated value of 40 per cent above may also be a lower limit. Combining our results with the star formation in ETGs, which is dominated by minor mergers (at least in low-density environments) and accounts for 14 per cent of cosmic star formation budget (K14), indicates that *around half the star formation activity at the present day is likely triggered by the minor-merger process.*

The observed correlation between galaxy stellar mass and the mass of the central black hole suggests that the enhanced star formation episodes triggered by minor mergers may also be accompanied by enhanced nuclear accretion. We have studied the specific accretion rate in 'early' (Sa) and 'late' (Sb and later types) spirals, by using the quantity L[O III]/σ^4, restricted to galaxies that are classified as Seyfert (in which the ionization is dominated by the central AGN). Mirroring the star formation results, the specific accretion rate is found to be enhanced in the disturbed spirals, with the enhancement higher in 'later' morphological types. However, the enhancement in nuclear accretion is not as pronounced as that found in the star formation activity, suggesting that star formation and nuclear accretion may not be tightly coupled in these minor-merger-enhanced episodes. This relatively weak correlation may be partly responsible for the larger intrinsic scatter in the stellar versus black hole mass correlation in spiral galaxies compared to their early-type counterparts.

Combined with the recent study of K14, the results of this paper further highlight the important (and still poorly quantified) role of minor mergers in influencing stellar mass and black hole growth in massive galaxies. While a significant fraction of star formation in *nearby* spirals is triggered by minor mergers, the role of this process is likely to become more significant with increasing redshift, both due to the gradually increasing merger rate (e.g. Lotz et al. 2011) and the higher gas fractions in massive galaxies at earlier epochs (e.g. Tacconi et al. 2010). At $z > 1$, and certainly around the epoch of peak cosmic star formation ($z \sim 2$), a significant number of disc galaxies are clumpy, gravitationally unstable systems (see e.g. Dekel, Sari & Ceverino 2009; Kereš et al. 2009; Ceverino, Dekel & Bournaud 2010; Devriendt et al. 2010), in which star formation could be efficiently triggered by minor mergers (e.g. Birnboim & Dekel 2003; Kereš et al. 2005; Dekel et al. 2009). Since discs form before bulges (e.g. Hatton et al. 2003), the lack of the stabilizing influence of a bulge may make these early discs even more susceptible to minor-merger-triggered star formation (e.g. Mihos & Hernquist 1994; Hernquist & Mihos 1995) compared to their modern-day counterparts.

Given the significance of this process in driving star formation, black hole growth and size evolution in massive galaxies, studying the role of minor mergers across a large range in redshift is essential. The most detailed insights are likely to come from high-resolution spatially resolved studies of local minor-merger remnants using the *Hubble Space Telescope* (*HST*), which employ sensitive tracers of star formation like the UV. As noted in the Introduction above, local star-forming ETGs are excellent initial laboratories for such spatially resolved analyses that probe the star formation laws associated with satellite accretion (Kaviraj et al., in preparation). At intermediate redshift ($z < 2$), the population of minor-merger remnants can be studied using the deep, high-resolution imaging offered by the *HST* (e.g. Kaviraj et al. 2011), in legacy fields such as CANDELS (e.g. Grogin et al. 2011; Koekemoer et al. 2011). At earlier epochs, this exercise will likely require deep, high-resolution imaging from future instruments like the Large Synoptic Survey Telescope (LSST) and the Extremely Large Telescopes. In any case, without a robust determination of minor-merger-driven stellar mass and black hole

growth over cosmic time, our understanding of galaxy evolution is likely to remain incomplete.

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REFERENCES

Abazajian K. N. et al., 2009, ApJS, 182, 543
Abraham R. G., Tanvir N. R., Santiago B. X., Ellis R. S., Glazebrook K., van den Bergh S., 1996, MNRAS, 279, L47
Baldwin J. A., Phillips M. M., Terlevich R., 1981, PASP, 93, 5
Barnes J. E., Hernquist L., 1992, ARA&A, 30, 705
Birnboim Y., Dekel A., 2003, MNRAS, 345, 349
Blanton M. R. et al., 2001, AJ, 121, 2358
Bluck A. F. L., Conselice C. J., Buitrago F., Grützbauch R., Hoyos C., Mortlock A., Bauer A. E., 2012, ApJ, 747, 34
Bournaud F., Jog C. J., Combes F., 2007, A&A, 476, 1179
Brinchmann J., Charlot S., White S. D. M., Tremonti C., Kauffmann G., Heckman T., Brinkmann J., 2004, MNRAS, 351, 1151
Bruzual G., Charlot S., 2003, MNRAS, 344, 1000
Buitrago F., Trujillo I., Conselice C. J., Bouwens R. J., Dickinson M., Yan H., 2008, ApJ, 687, L61
Carpineti A., Kaviraj S., Darg D., Lintott C., Schawinski K., Shabala S., 2012, MNRAS, 420, 2139
Ceverino D., Dekel A., Bournaud F., 2010, MNRAS, 404, 2151
Charlot S., Fall S. M., 2000, ApJ, 539, 718
Charlot S., Longhetti M., 2001, MNRAS, 323, 887
Cimatti A., Nipoti C., Cassata P., 2012, MNRAS, 422, L62
Cole S., Lacey C. G., Baugh C. M., Frenk C. S., 2000, MNRAS, 319, 168
Cole S. et al., 2001, MNRAS, 326, 255
Conselice C. J., Bershady M. A., Dickinson M., Papovich C., 2003, AJ, 126, 1183
Cox T. J., Dutta S. N., Di Matteo T., Hernquist L., Hopkins P. F., Robertson B., Springel V., 2006, ApJ, 650, 791
Cox T. J., Jonsson P., Somerville R. S., Primack J. R., Dekel A., 2008, MNRAS, 384, 386
Crockett R. M. et al., 2011, ApJ, 727, 115
Daddi E. et al., 2005, ApJ, 626, 680
Damjanov I. et al., 2009, ApJ, 695, 101
Darg D. W. et al., 2010a, MNRAS, 401, 1043
Darg D. W. et al., 2010b, MNRAS, 401, 1552
de Vaucouleurs G., 1959, Handbuch Phys., 53, 275
Dekel A., Sari R., Ceverino D., 2009, ApJ, 703, 785
Devriendt J. et al., 2010, MNRAS, 403, L84
Di Matteo T., Colberg J., Springel V., Hernquist L., Sijacki D., 2008, ApJ, 676, 33
Dressler A., 1984, ARA&A, 22, 185
Ellison S. L., Patton D. R., Simard L., McConnachie A. W., 2008, AJ, 135, 1877
Fakhouri O., Ma C.-P., 2008, MNRAS, 386, 577
Fan L., Lapi A., De Zotti G., Danese L., 2008, ApJ, 689, L101
Ferrarese L., Merritt D., 2000, ApJ, 539, L9
Frieman J. A. et al., 2008, AJ, 135, 338
Fukugita M. et al., 2007, AJ, 134, 579
Gebhardt K. et al., 2000, ApJ, 543, L5
Grogin N. A. et al., 2011, ApJS, 197, 35
Gültekin K. et al., 2009, ApJ, 698, 198
Hatton S., Devriendt J. E. G., Ninin S., Bouchet F. R., Guiderdoni B., Vibert D., 2003, MNRAS, 343, 75
Heckman T. M., Kauffmann G., Brinchmann J., Charlot S., Tremonti C., White S. D. M., 2004, ApJ, 613, 109
Hernquist L., 1989, Nature, 340, 687

Hernquist L., Mihos J. C., 1995, ApJ, 448, 41
Ho L. C., Filippenko A. V., Sargent W. L. W., 1993, ApJ, 417, 63
Hopkins P. F., Hernquist L., Cox T. J., Kereš D., 2008, ApJS, 175, 356
Hopkins P. F., Bundy K., Murray N., Quataert E., Lauer T. R., Ma C.-P., 2009, MNRAS, 398, 898
Hubble E. P., 1926, ApJ, 64, 321
Huertas-Company M. et al., 2013, MNRAS, 428, 1715
Jesseit R., Naab T., Peletier R. F., Burkert A., 2007, MNRAS, 376, 997
Jogee S. et al., 2009, ApJ, 697, 1971
Kannappan S. J., 2004, ApJ, 611, L89
Kauffmann G. et al., 2003, MNRAS, 341, 33
Kaviraj S., 2010, MNRAS, 406, 382
Kaviraj S., 2014, MNRAS, 437, L41 (K14)
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.-M., Ellis R. S., Silk J., 2011, MNRAS, 411, 2148
Kereš D., Katz N., Weinberg D. H., Davé R., 2005, MNRAS, 363, 2
Kereš D., Katz N., Fardal M., Davé R., Weinberg D. H., 2009, MNRAS, 395, 160
Kewley L. J., Groves B., Kauffmann G., Heckman T., 2006, MNRAS, 372, 961
Khochfar S., Silk J., 2006, MNRAS, 370, 902
Kimm T., Yi S. K., Khochfar S., 2011, ApJ, 729, 11
Knapen J. H., Whyte L. F., de Blok W. J. G., van der Hulst J. M., 2004, A&A, 423, 481
Koekemoer A. M. et al., 2011, ApJS, 197, 36
Komatsu E. et al., 2011, ApJS, 192, 18
Li C., Kauffmann G., Heckman T. M., Jing Y. P., White S. D. M., 2008, MNRAS, 385, 1903
Lin L. et al., 2004, ApJ, 617, L9
Lintott C. J. et al., 2008, MNRAS, 389, 1179
Lintott C. et al., 2011, MNRAS, 410, 166
López-Sanjuan C., Balcells M., Pérez-González P. G., Barro G., Gallego J., Zamorano J., 2010, ApJ, 710, 1170
Lotz J. M., Primack J., Madau P., 2004, AJ, 128, 163
Lotz J. M., Jonsson P., Cox T. J., Croton Darren., Primack J. R., Somerville R. S., Stewart K., 2011, ApJ, 742, 103
McConnell N. J., Ma C.-P., Gebhardt K., Wright S. A., Murphy J. D., Lauer T. R., Graham J. R., Richstone D. O., 2011, Nature, 480, 215
Magorrian J. et al., 1998, AJ, 115, 2285
Maller A. H., Katz N., Kereš D., Davé R., Weinberg D. H., 2006, ApJ, 647, 763
Martig M., Bournaud F., Teyssier R., Dekel A., 2009, ApJ, 707, 250
Mazzuca L. M., Sarzi M., Knapen J. H., Veilleux S., Swaters R., 2006, ApJ, 649, L79
Merritt D., Ferrarese L., 2001, ApJ, 547, 140
Mihos J. C., Hernquist L., 1994, ApJ, 425, L13
Moore B., Lake G., Quinn T., Stadel J., 1999, MNRAS, 304, 465
Naab T., Jesseit R., Burkert A., 2006, MNRAS, 372, 839
Naab T., Johansson P. H., Ostriker J. P., 2009, ApJ, 699, L178
Nair P. B., Abraham R. G., 2010, ApJS, 186, 427
Newman A. B., Ellis R. S., Bundy K., Treu T., 2012, ApJ, 746, 162
Nipoti C., Treu T., Auger M. W., Bolton A. S., 2009, ApJ, 706, L86
Oser L., Naab T., Ostriker J. P., Johansson P. H., 2012, ApJ, 744, 63
Patton D. R., Torrey P., Ellison S. L., Mendel J. T., Scudder J. M., 2013, MNRAS, 433, L59
Peirani S., Crockett R. M., Geen S., Khochfar S., Kaviraj S., Silk J., 2010, MNRAS, 405, 2327
Poggianti B. M., Barbaro G., 1997, A&A, 325, 1025
Rix H.-W. et al., 2004, ApJS, 152, 163
Robaina A. R. et al., 2009, ApJ, 704, 324
Robertson B., Bullock J. S., Cox T. J., Di Matteo T., Hernquist L., Springel V., Yoshida N., 2006, ApJ, 645, 986
Ryan R. E., Jr et al., 2012, ApJ, 749, 53
Saintonge A. et al., 2012, ApJ, 758, 73

Saracco P., Longhetti M., Andreon S., 2009, MNRAS, 392, 718

Sarzi M. et al., 2010, MNRAS, 402, 2187

Schawinski K., Thomas D., Sarzi M., Maraston C., Kaviraj S., Joo S.-J., Yi S. K., Silk J., 2007, MNRAS, 382, 1415

Schweizer F., Seitzer P., 1992, AJ, 104, 1039

Schweizer F., Seitzer P., Faber S. M., Burstein D., Dalle Ore C. M., Gonzalez J. J., 1990, ApJ, 364, L33

Scudder J. M., Ellison S. L., Torrey P., Patton D. R., Mendel J. T., 2012, MNRAS, 426, 549

Shabala S. S. et al., 2012, MNRAS, 423, 59

Shankar F., Marulli F., Mathur S., Bernardi M., Bournaud F., 2012, A&A, 540, 23

Smith D. A. et al., 1996, ApJ, 473, L21

Somerville R. S., Primack J. R., 1999, MNRAS, 310, 1087

Springel V., Di Matteo T., Hernquist L., 2005, MNRAS, 361, 776

Stewart K. R., Bullock J. S., Wechsler R. H., Maller A. H., Zentner A. R., 2008, ApJ, 683, 597

Tacconi L. J. et al., 2010, Nature, 463, 781

Toomre A., 1977, in Tinsley B. M., Larson R. B., eds, Evolution of Galaxies and Stellar Populations. Yale University Observatory, New Haven, p. 401

Toomre A., Toomre J., 1972, ApJ, 178, 623

Tremonti C. A. et al., 2004, ApJ, 613, 898

Trujillo I. et al., 2006, ApJ, 650, 18

Trujillo I., Ferreras I., de La Rosa I. G., 2011, MNRAS, 415, 3903

van Dokkum P. G. et al., 2008, ApJ, 677, L5

Veilleux S., Osterbrock D. E., 1987, ApJS, 63, 295

White S. D. M., 1978, MNRAS, 184, 185

Yi S. K. et al., 2005, ApJ, 619, L111

York D. G. et al., 2000, AJ, 120, 1579

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