Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 31 July 2015 (MN LaTeX style file v2.2)

Galaxy Zoo: Evidence for rapid, recent quenching across a population of AGN host galaxies

R. J. Smethurst,[1] C. J. Lintott,[1] B. D. Simmons,[1] K. Schawinski,[2]
S. P. Bamford,[3] C. N. Cardamone,[4] S. J. Kruk,[1] K. L. Masters,[5]
C. M. Urry,[6] K. W. Willett,[7] O. I. Wong[8] ⋆

[1] *Oxford Astrophysics, Department of Physics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford, OX1 3RH, UK*
[2] *Institute for Astronomy, Department of Physics, ETH Zurich, Wolfgang-Pauli Strasse 27, CH-8093 Zürich, Switzerland*
[3] *School of Physics and Astronomy, The University of Nottingham, University Park, Nottingham, NG7 2RD, UK*
[4] *Math & Science Department, Wheelock College, 200 The Riverway, Boston, MA 02215, USA*
[5] *Institute of Cosmology and Gravitation, University of Portsmouth, Dennis Sciama Building, Barnaby Road, Portsmouth, PO1 3FX, UK*
[6] *Department of Physics and Yale Center for Astronomy and Astrophysics, Yale University, PO Box 208121, New Haven, CT 06520-8121, USA*
[7] *School of Physics and Astronomy, University of Minnesota, 116 Church St SE, Minneapolis, MN 55455, USA*
[8] *International Centre for Radio Astronomy Research, UWA, 35 Stirling Highway, Crawley, WA 6009, Australia*

31 July 2015

ABSTRACT

We present a population study of the star formation history of $1,244$ Type 2 AGN host galaxies, compared to $123,243$ inactive galaxies using a Bayesian method. We find evidence for the Type 2 AGN host galaxies having undergone a recent (within 2 Gyr) and rapid (exponential rate $\tau < 1$ Gyr) drop in their star formation rate. AGN feedback is therefore important at least for this population of galaxies. This result is not seen for the inactive galaxies whose star formation histories are dominated by the effects of downsizing at earlier epochs, a secondary effect for the AGN host galaxies. We show that histories of rapid quenching cannot account fully for the quenching of all the star formation in a galaxy's lifetime across the population of AGN host galaxies, and that histories of slower quenching, attributed to secular evolution, are also key in their evolution. This is in agreement with recent results showing both merger-driven and non-merger processes are contributing to the co-evolution of galaxies and supermassive black holes. The availability of gas in the reservoirs of a galaxy, and its ability to be replenished, appear to be the key drivers behind this co-evolution.

1 INTRODUCTION

The nature of the observed co-evolution of galaxies and their central supermassive black holes (Magorrian et al. 1998; Marconi & Hunt 2003; Haring & Rix 2004) and the effects of AGN feedback on galaxies are two of the most important open issues in galaxy evolution. AGN feedback was first suggested as a mechanism for regulating star formation in simulations (Silk & Rees 1998; Croton et al. 2006; Bower et al. 2006; Somerville et al. 2008) and some indirect evidence has been observed for both positive and negative feedback in various systems (see the comprehensive review from Fabian 2006).

The strongest observational evidence for AGN feedback in a population is that the largest fraction of AGN are found in the green valley (Cowie & Barger 2008; Hickox et al. 2009; Schawinski et al. 2010), suggesting some link between AGN activity and the process of quenching which moves a galaxy from the blue cloud to the red sequence. However, concrete statistical evidence for the effect of AGN feedback on the host galaxy population has so far been elusive.

Here we present a large observational population study of the quenching of the host galaxies of Type 2 AGN identified by line diagnostics. We use a new Bayesian method[1] (Smethurst et al. 2015) to effectively model the SFH of a galaxy with two parameters, time of quenching, t_q, and exponential rate, τ, given the observed near ultra-violet (NUV) and optical colours. We aim to determine the following: (i) Are galaxies currently hosting an AGN undergoing quenching? (ii) If so, when and at what rate does this quenching occur? (iii) Is this quenching occurring at different times and rates compared to a control sample of inactive galaxies?

The zero points of all magnitudes are in the AB system and where necessary, we adopt the WMAP Seven-

⋆ This investigation has been made possible by the participation of more than 350,000 users in the Galaxy Zoo project. Their contributions are individually acknowledged at `http://authors.galaxyzoo.org`

[1] Publicly available: `http://github.com/zooniverse/starpy`

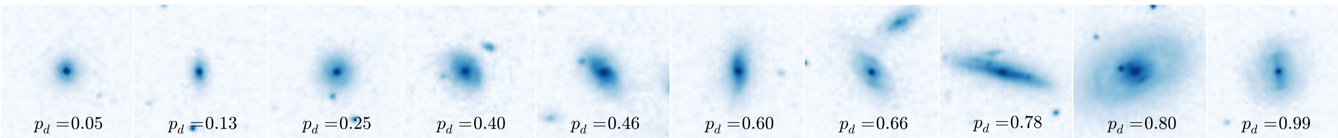

Figure 1. Randomly selected SDSS *gri* composite images from the sample of $1,244$ Type 2 AGN in a redshift range $0.04 < z < 0.05$. The galaxies are ordered from least to most featured according to their debiased 'disc or featured' vote fraction, p_d (see Willett et al. 2013). The scale for each image is 0.099 arcsec/pixel.

Year Cosmology (Jarosik et al. 2011) with $(\Omega_m,\ \Omega_\Lambda,\ h) = (0.26, 0.73, 0.71)$.

2 DATA & METHODS

In this investigation we use visual classifications of galaxy morphologies from the Galaxy Zoo 2[2] (GZ2) citizen science project (Willett et al. 2013), which obtains multiple independent classifications for each optical image. The full question tree for an image is shown in Figure 1 of Willett et al. The GZ2 project used $304,022$ images from the Sloan Digital Sky Survey Data Release 7 (SDSS; York et al. 2000; Abazajian et al. 2009) all classified by *at least* 17 independent users, with a mean number of classifications of ~ 42.

Further to this, we required NUV photometry from the GALEX survey, within which $\sim 42\%$ of the GZ2 sample was observed, giving $126,316$ galaxies total ($0.01 < z < 0.25$). This will be referred to as the GZ2-GALEX sample. The completeness of this sample ($-22 < M_u < -15$) is shown in Figure 2 of Smethurst et al. (2015) with the u-band absolute magnitude against redshift for this sample in comparison to the SDSS data set.

2.1 Bayesian SFH Determination

STARPY[3] is a PYTHON code which allows the user to derive the quenched star formation history (SFH) of a galaxy through a Bayesian Markov Chain Monte Carlo method (Foreman-Mackey et al. 2013)[4] with the input of the observed $u-r$ and $NUV-u$ colours, a redshift, and the use of the stellar population models of Bruzual & Charlot (2003). The star formation history template is an exponential decline of the SFR and is described by two parameters $[t_q, \tau]$, where t_q is the time at which the onset of quenching begins [Gyr] and τ is the exponential rate at which quenching occurs [Gyr]. Under the simplifying assumption that all galaxies formed at $t = 0$ Gyr with an initial burst of star formation, the SFH can be described as:

$$SFR = \begin{cases} i_{sfr}(t_q) & \text{if } t < t_q \\ i_{sfr}(t_q) \times exp\left(\frac{-(t-t_q)}{\tau}\right) & \text{if } t > t_q \end{cases} \qquad (1)$$

where i_{sfr} is an initial constant star formation rate dependent on t_q (Schawinski et al. 2014; Smethurst et al. 2015). A smaller τ value corresponds to a rapid quench, whereas a larger τ value corresponds to a slower quench. The output of STARPY is probabilistic in nature and provides the posterior probability distribution across the entirety of the two parameter space for each individual galaxy. The probabilistic fitting methods to this SFH for an observed galaxy are described in full detail in Smethurst et al. (2015) wherein the STARPY code was used to characterise the SFHs of the GZ2-GALEX sample.

2.2 AGN Sample

We selected Type 2 AGN using a BPT diagram (Baldwin, Phillips & Terlevich 1981) using line and continuum strengths for [OIII], [NII], [SII] and [OII] obtained from the MPA-JHU catalogue (Kauffman et al. 2003a; Brinchmann et al. 2004) for galaxies in the GZ2-GALEX sample. We then required the S/N > 3 for each emission line as in Schawinski et al. (2010). Those galaxies which satisfied all of the inequalities defined in Kewley et al. (2001) and Kauffman et al. (2003b) were selected as Type 2 AGN, giving $1,299$ host galaxies ($\sim 10\%$ of the GZ2-GALEX sample). Sarzi et al. (2010); Yan & Blanton (2012) and Singh et al. (2013) have all demonstrated that LINERs are not primarily powered by AGN, therefore for purity, we excluded these galaxies from the sample using the definition from Kewley et al. (2006) (55 galaxies total) with no change to the results. These $1,244$ galaxies will be referred to as the AGN-HOST sample.

Type 2 AGN were used in this analysis as opposed to Type 1 due to their photometric obscuration. Type 1 AGN contaminate their galaxy's photometric measurements which would need to be removed through aperture matching. Due to the requirement for NUV colours from GALEX, in order to be sensitive to any recent star formation, the aperture matching to SDSS becomes a non-trivial task.

Simmons et al. (2011) showed that the obscuration of a Type 2 AGN is more efficient in the NUV than in the optical. Residual NUV flux from the AGN can thus be neglected in comparison to that of the galaxy. However there is often some residual optical flux that can affect the measurements of the host galaxy's photometry. We can subtract this central optical AGN flux using the PSF magnitudes provided by SDSS (the aperture containing the central flux of a galaxy), however the change in the colours of these galaxies after this correction is negligible, with $\Delta(u-r) \sim 0.09$. We therefore use the uncorrected colours to avoid unnecessary complexity and minimise the propagation of uncertainty from the colours through to the SFHs. Including these corrected colours does not change the results described below.

Images from SDSS for ten randomly selected Type 2 AGN host galaxies from this sample are shown in Figure 1 and the entire sample is shown in Figure 2 with those galaxies selected as Type 2 AGN marked in red and the matched GZ2-GALEX galaxies in black. For

[2] http://zoo2.galaxyzoo.org/
[3] Publicly available: http://github.com/zooniverse/starpy
[4] http://dan.iel.fm/emcee/

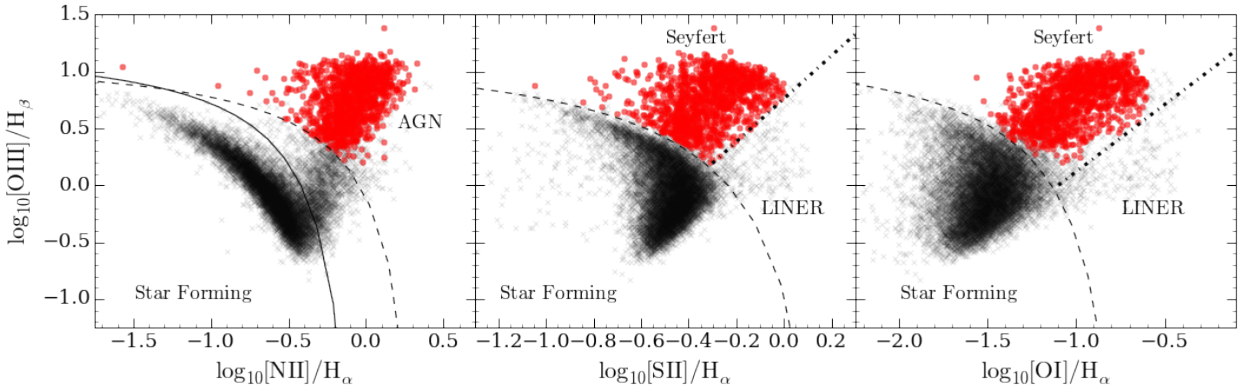

Figure 2. BPT diagrams for galaxies in the GZ2-GALEX sample (black crosses) with S/N > 3 for each emission line. Inequalities defined in: Kewley et al. (2001) to separate SF galaxies from AGN (dashed lines), Kauffman et al. (2003b) to separate SF from composite SF-AGN galaxies (solid line) and Kewley et al. (2006) to separate LINERS and Seyferts (dotted lines). Galaxies are included in the AGN-HOST sample (red circles) if they satisfy all the inequalities to be classified as Seyferts. LINERs are excluded for purity.

this sample the mean $\log L[OIII]$ [erg s^{-1}] $\sim$ 41.3 and median $\log L[OIII]$ [erg s^{-1}] $\sim$ 41.0, with a range of $\log L[OIII]$ [erg s^{-1}] luminosities of $39.4 - 43.0$.

We constructed a sample of inactive galaxies by removing from the GZ2-GALEX sample all galaxies in the AGN-HOST sample, as well as sources identified as Type 1 AGN by the presence of broad emission lines (Oh et al. 2015). We refer to this sample as the INACTIVE sample. A Kolmogorov-Smirnov test revealed the redshift distributions of the INACTIVE and AGN-HOST samples are statistically indistinguishable ($D \sim 0.16$, $p \sim 0.88$).

Since this investigation is focussed on whether an AGN can have an impact on the SF of its host galaxy, we must consider whether there is a selection effect present in this identification method. The extent to which SF could be obscured by AGN emission was addressed by Schawinski et al. (2010). They showed, through a simple empirical experiment which simulated the addition of an AGN of known luminosity to a star forming galaxy, that BPT-based selection of AGN produces a complete sample, even in the blue cloud, at luminosities of $L[OIII] > 10^{40}$erg s^{-1}. Above this limit we therefore assume we have selected a complete sample of AGN independent of host galaxy SFR.

We also split both the AGN-HOST and INACTIVE samples into low, medium and high mass ranges (see Table 1) to investigate any trends in the SFH with mass. Masses were calculated using the $(u-r)$ colour and absolute r-band magnitude with the method outlined in Baldry et al. (2006).

3 RESULTS

We apply the method outlined in Section 2.1 to obtain a 2-dimensional likelihood distribution across the $[t_q, \tau]$ parameter space. We combine individual galaxy likelihood distributions within the AGN-HOST and INACTIVE galaxy samples, additionally weighting by GZ2 morphologies to produce quenching parameter likelihood distributions for both disc- and smooth-dominated galaxy populations in the three mass bins defined in Table 1. Schawinski et al. (2014) showed the morphological dependance of quenching histories therefore it is important to distinguish by morphological type.

Table 1. Table showing the number of galaxies in each of the three mass bins for both the AGN-HOSTS and INACTIVE galaxy samples.

Mass Bin	AGN-HOSTS	INACTIVE
$\log[M_*/M_\odot] < 10.25$	165 (13.3%)	41197 (33.4%)
$10.25 < \log[M_*/M_\odot] < 10.75$	630 (50.6%)	46428 (37.7%)
$\log[M_*/M_\odot] > 10.75$	449 (36.1%)	35618 (28.9%)

These 2-dimensional likelihoods are summed across each parameter axis and normalised to produce the one dimensional histograms shown in Figures 3 and 4 for the quenching time, t_q and exponential quenching rate, τ, respectively. In each figure the summed 1-dimensional normalised probability distribution across the given parameter is shown for smooth and disc dominated galaxies across three mass bins for the AGN-HOST and INACTIVE samples. In Figure 4 the percentage likelihoods in each region of quenching rate, shown by the dashed lines for rapid ($\tau < 1$ Gyr), intermediate ($1 < \tau$ [Gyr] < 2) and slow ($\tau > 2$ Gyr) quenching timescales, are shown.

It is immediately apparent from Figures 3 and 4 that there is a distinct difference between the distribution of likelihood for AGN-HOST and INACTIVE populations.

At all masses, the distribution of likelihood for the AGN-HOST population across the quenching time t_q parameter (left panels of Figure 3) is different from that of the inactive galaxies (right panels of Figure 3). Recent quenching ($t >$ 11 Gyr) of AGN-HOST galaxies is the dominant history for low and medium mass galaxies, particularly for the smooth dominated population. However, this effect is less dominant in higher mass galaxies where quenching at earlier times has significant likelihood.

The distributions of likelihood for the quenching rate, τ, in Figure 4 show the dominance of rapid quenching ($\tau < 1$ Gyr) across the AGN-HOST population, particularly for smooth galaxies. With increasing mass the dominant quenching rate becomes slow ($\tau > 2$ Gyr) especially for disc galaxies hosting an AGN. Similar trends in likelihood are

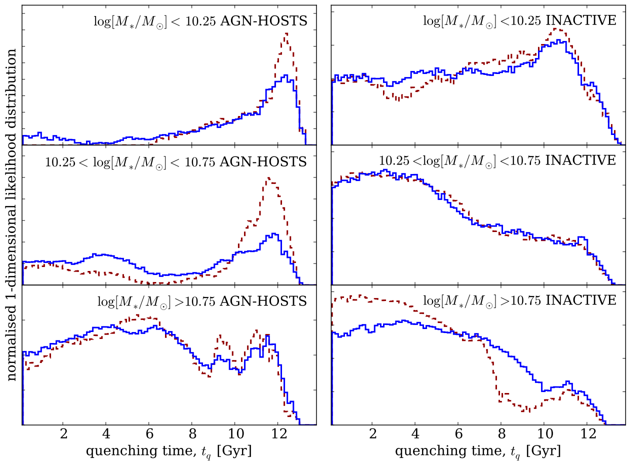

Figure 3. Likehood distribution for the quenching time, t_q parameter normalised so that the areas under the curves are equal. AGN-HOST (left) and INACTIVE (right) galaxies are split into low (top), medium (middle) and high (bottom) mass for smooth (red dashed) and disc (blue solid) galaxies. A low value of t_q corresponds to the early Universe and a high value to the recent Universe.

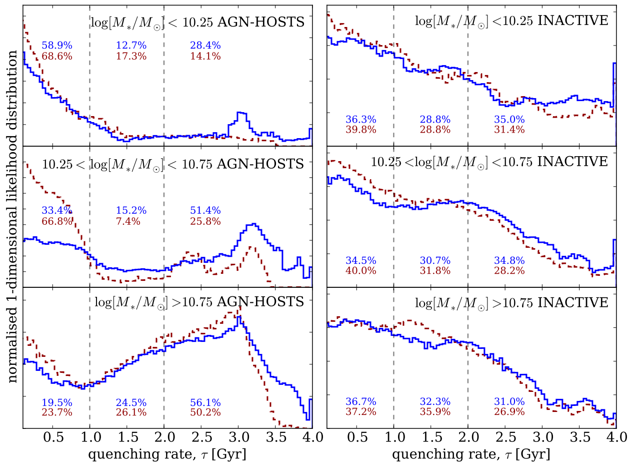

Figure 4. Likehood distribution for the quenching rate, τ normalised so that the areas under the curves are equal. AGN-HOST (left) host and INACTIVE (right) galaxies are split into low (top), medium (middle) and high (bottom) mass for smooth (red dashed) and disc (blue solid) galaxies. The black dashed lines show the separation between rapid (τ < 1.0 Gyr), intermediate (1.0 < τ [Gyr] < 2.0) and slow (τ > 2.0 Gyr) quenching timescales with the percentage likelihood distribution in each region for disc (blue) and smooth (red) populations. A small (large) value of τ corresponds to a rapid (slow) quench.

observed for the INACTIVE population but the overall distribution of likelihood is very different.

The likelihood distribution for the AGN-HOST galaxies therefore shows evidence for the dominance of rapid, recent quenching having occurred across the entire population. This result implies the importance of AGN feedback for the evolution of these galaxies.

4 DISCUSSION

The differences between the distribution of likelihood for the AGN-HOST and INACTIVE galaxy populations reveal that an AGN can have a significant effect on the SFH of its host galaxy. Both recent, rapid quenching and early, slow quenching are observed in the likelihood distribution of the AGN-HOST population.

The difference between the AGN-HOST and INACTIVE population distribution of likelihood in Figure 4 for the rate of quenching, τ, tells a story of gas reservoirs. The distribution of probability for higher mass AGN-HOST galaxies is dominated by slower, early quenching implying another mechanism is responsible for the cessation of star formation in these high mass galaxies prior to the triggering of the current AGN. This preference for slower evolution timescales follows from the ideas of previously isolated discs evolving slowly by the Kennicutt-Schmidt (Schmidt 1959; Kennicutt 1997) law which can then undergo an interaction or merger to reinvigorate star formation, feed the central black hole and trigger a current AGN (Varela et al. 2004; Emsellem et al. 2015). These galaxies would need a large enough gas reservoir to fuel both SF throughout their lifetimes and the recent AGN. These high mass galaxies also play host to the most luminous AGN (mean $\log L[OIII][\mathrm{erg\,s^{-1}}] \sim 41.6$) and so this SFH challenges the typical merger-driven theory for the co-evolution of the most luminous black holes and their host galaxies.

Quenching at early times is also observed for the INACTIVE population, where the likelihood distribution for the quenching time is roughly constant until recent times where the distribution drops off. This drop-off occurs at earlier times with increasing mass (right panels Figure 3). This is evidence of downsizing across the entire INACTIVE galaxy population whereby stars in massive galaxies form first and quench early (Cowie et al. 1996; Thomas et al. 2010).

The most massive smooth AGN-HOST galaxies also show a preference for earlier quenching (bottom left panel Figure 3) occurring at slow rates; we speculate that this is also due to the effects of downsizing rather than being caused by the current AGN. This earlier evolution would first form a slowly 'dying' or 'dead' galaxy typical of massive elliptical galaxies which can then have a recent infall of gas either through a minor merger, galaxy interaction or environmental change, triggering further star formation and feeding the central black hole, triggering an AGN (Kaviraj et al. 2014). In turn this AGN can then quench the recent boost in star formation. This track is similar to the evolution history proposed for blue ellipticals (Kaviraj et al. 2013; McIntosh et al. 2014; Haines et al. 2015). This SFH would then give rise to the distribution of the likelihood seen across the high mass AGN-HOST population for both time and rate parameters.

These recently triggered AGN in both massive disc and smooth galaxies do not have have the ability to impact the SF across the entirety of such a high mass galaxy in a deep gravitational potential (Ishibashi et al. 2012; Zinn et al. 2013). This leads to the less dominant peak for recent, rapid quenching in the high mass AGN-HOST population for both morphologies.

Conversely, rapid quenching, caused by the AGN itself through negative feedback, is the most dominant history for low mass AGN-HOST galaxies with lower gravitational potentials which allow gas to be expelled more easily (or heated by the AGN) across the entire galaxy (Tortora et al. 2009).

Tortora et al. (2009) model the effects of negative AGN feedback on a typical early type (i.e. smooth) galaxy and find the time between the current galaxy age in their simulation, t_{gal} and the time that the feedback began, t_{AGN}, peaks at $t_{gal} - t_{AGN} \sim 0.85$ Gyr. This agrees with the location of the peak in Figure 3 for low mass galaxies, where the difference between the peak of the likelihood and the average age of the population (galaxy age is calculated from the redshift by assuming all galaxies form at $t = 0$) is ~ 0.83 Gyr. This implies that this dominant recent quenching history is caused directly by AGN feedback, as opposed to the AGN being a consequence of an alternative quenching mechanism.

Rapid quenching is particularly dominant for low-to-medium mass smooth galaxies. Smethurst et al. (2015) suggest that incredibly rapid quenching rates could be attributed to mergers of galaxies in conjunction with AGN feedback, which are thought to be responsible for creating the most massive smooth galaxies (Conselice et al. 2003; Springel, Di Matteo & Hernquist 2005; Hopkins et al. 2008). This dominance of rapid quenching across the smooth AGN-HOST population supports the idea that a merger, having caused a morphological transformation to a smooth galaxy, can also trigger an AGN, causing further feedback and cessation of star formation (see Figure 14 of Schawinski et al. 2014).

For the medium mass AGN-HOST population we see a bimodal distribution of likelihood between these two dominant quenching histories, highlighting the strength of this method which is capable of detecting such variation in the SFHs across a population of galaxies.

We have used morphological classifications from the Galaxy Zoo 2 project to determine the morphology-dependent star formation histories of a population of 1,244 Type 2 Seyfert AGN host galaxies, in comparison to an inactive galaxy population, via a Bayesian analysis of an exponentially declining star formation history model. We determined the most likely parameters for the quenching onset time, t_q, and exponential quenching rate, τ, and find clear differences in the combined population likelihoods between inactive and AGN host galaxy populations. We have demonstrated a clear dependence on a galaxy currently hosting an AGN and its SFR. There is strong evidence for downsizing in massive inactive galaxies, which appears as a secondary effect in AGN host galaxies. The dominant quenching mechanism for galaxies currently hosting an AGN is for rapid quenching which has occurred very recently. This result demonstrates the importance of AGN feedback across the entire host galaxy population, in driving the evolution of galaxies across the colour-magnitude diagram.

ACKNOWLEDGEMENTS

RS acknowledges funding from the STFC Grant Code ST/K502236/1. BDS gratefully acknowledges support from Balliol College, Oxford. KS gratefully acknowledges support from Swiss National Science Foundation Grant PP00P2_138979/1. SJK acknowledges funding from the STFC Grant Code ST/MJ0371X/1. KLM acknowledges funding from The Leverhulme Trust as a 2010 Early Career Fellow. KWW acknowledges funding from NSF grant AST-1413610. OIW acknowledges a Super Science Fellowship from the Australian Research Council. The authors would like to thank S. Kaviraj for helpful discussions. The development of Galaxy Zoo was supported in part by the Alfred P. Sloan Foundation and The Leverhulme Trust. Based on observations made with the NASA Galaxy Evolution Explorer[5] and the SDSS[6].

REFERENCES

Abazajian, K. N. et al., 2009, ApJS, 182, 543
Baldry, I. et al., 2006, MNRAS, 373, 469
Baldwin, J. A., Phillips, M. M., & Terlevich, R. 1981, PASP, 93, 5
Bamford, S. et al., 2009, MNRAS, 393, 1324
Bower, R. et al., 2006, MNRAS, 370, 645
Brinchmann, J. et al., 2004, MNRAS, 351, 1151
Bruzual, G. & Charlot, S., 2003, MNRAS, 344, 1000
Cisternas, M. et al., 2011, ApJ, 726, 57
Conselice, C. J. et al., 2003, AJ, 126, 1183
Cowie, L. et al., 1996, AJ, 112, 839
Cowie, L. & Barger, A. J., 2008, ApJ, 686, 72
Croton, D. J. et al., 2006, MNRAS, 365, 11
Emsellem, E. et al. 2015, MNRAS, 446, 2468
Fabian, A. C. 2006, ARA&A, 50, 455
Foreman-Mackey, D., Hogg, D. W., Lang, D., Goodman, J., 2013, PASP, 125, 306
Haines, T. et al., 2015, arXiv:1505.01493
Haring, N. & Rix, H-W., 2004, ApJ, 604, 89
Hickox, R. C., et al., 2009, ApJ, 696, 891
Hopkins, F. et al., 2008, ApJSS, 175, 390
Ishibashi, W. et al., 2012, MNRAS, 427, 2998
Kauffman, G. et al., 2003, MNRAS, 341, 33
Kauffman, G. et al., 2003, MNRAS, 346, 1055
Kaviraj, S. et al., 2013, MNRAS, 428, 925
Kaviraj, S. et al., 2014, MNRAS, 440, 2944
Kennicutt, R. C., 1997, ApJ, 498, 491
Kewley, L. J. et al., 2001, ApJ, 556, 121
Kewley, L. J. et al., 2006, MNRAS, 372, 961
Kormendy, J. & Kennicutt, R. J., 2004, ARA&A, 42, 603
Lintott, C. J. et al., 2011, MNRAS, 410, 166
Magorrian, J. et al., 1998, AJ, 115, 2285
Marconi, A. & Hunt, L. K., 2003, ApJ, 589, 21
McIntosh, D. et al., 2014, MNRAS, 442, 533
Oh, K. et al. 2015, arXiv: 1504.07247
Yan, R. & Blanton, M. R. 2012, ApJ, 747, 61
Sarzi, M. et al., 2010, MNRAS, 402, 2187
Schawinski, K. et al., 2010, MNRAS, 711, 284
Schawinski, K. et al., 2014, MNRAS, 440, 889
Schmidt, M., 1959, ApJ, 129, 243
Silk, J. & Rees, M. J., 1998, A&A, 331, L1
Simmons, B. D. et al., 2011, ApJ, 734, 121
Singh, R. et al., 2013, A&A, 558, 43
Smethurst, R. J. et al., 2015, MNRAS, 450, 435
Somerville, R. S. et al., 2008, MNRAS, 391, 481

[5] `http://galex.stsci.edu/GR6/`
[6] `https://www.sdss3.org/collaboration/boiler-plate.php`

Springel, V., Di Matteo, T. & Hernquist, L., 2005, ApJ, 620, L79
Taylor, M. B., 2005, ASP Conference Series, 347
Thomas, D. et al., 2010, MNRAS, 404, 1775
Tortora, C. et al., 2009, MNRAS, 369, 61
Varela, J. et al., 2004, A&A, 420, 873
Willett, K. et al., 2013, MNRAS, 435, 2835
York, D. G. et al., 2000, AJ, 120, 1579
Zinn, P. et al., 2013, ApJ, 774, 66