

Galaxy Zoo: Evidence for quenching caused by AGN feedback

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ABSTRACT

We present the first observational population study of the star formation history (SFH) of AGN host galaxies, in comparison with a population of inactive galaxies using a Bayesian method and a sample of 1,299 Type 2 AGN. We find evidence for a population of Type 2 AGN host galaxies to have undergone recent and rapid drop in their star formation rate. This result is not seen for the population of inactive galaxies whose SFHs are dominated by the effects of downsizing at earlier epochs; a secondary effect for the AGN host galaxies. We show that rapid quenching histories cannot account fully for the quenching of all the star formation across the population of AGN host galaxies and that slower quenching histories, attributed to non-violent processes of evolution are also key in their evolution. This is against the typically accepted merger driven scenario of the co-evolution of black holes and their galaxies. The availability, and ability to be replenished, of gas in the reservoirs of a galaxy is the key driver behind this co-evolution.

1 INTRODUCTION

Two of the most important issues in current astrophysical understanding are: (i) the co-evolution of galaxies and their central black holes and (ii) the effects, if any, of AGN feedback. There is an obvious relationship between the evolution of a central black hole and its host galaxy, observed multiple times and commonly referred to as the Magorrian relationship (Magorrian et al. 1998; Marconi & Hunt 2003; Haring & Rix 2004). AGN feedback was first theorised as a mechanism for regulating star formation in simulations (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 this feedback 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 to the process of quenching star formation in order for a galaxy to progress from the blue cloud to the red sequence. However concrete statistical evidence for the effect of AGN feedback on the host galaxy population has not been found.

Here we present the first large observational population study of the quenching of the host galaxies of Type 2

AGN, with the use of a new PYTHON routine, STARPY, implementing a Bayesian method to effectively model the SFH of a galaxy with two parameters, time of quenching and exponential rate, given the observed near ultra-violet (NUV) & optical colours. We therefore 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?

This letter proceeds as follows. Section 2 contains a description of the sample data, and details of the Bayesian analysis of an exponentially declining star formation history model. Section 3 contains the results produced by this analysis, with Section 4 providing a detailed discussion and a summary of the results obtained. The zero points of all ugriz magnitudes are in the AB system and where necessary we adopt the WMAP Seven-Year Cosmological parameters (Jarosik et al. 2011) with $(\Omega_m, \Omega_\lambda, h) = (0.26, 0.73, 0.71)$.

2 DATA & METHODS

2.1 Galaxy Zoo 2

In this investigation we use visual classifications of galaxy morphologies from the Galaxy Zoo 2¹ citizen science project (Willett et al. 2013), which obtains multiple independent classifications for each optical galaxy image; the full question tree for each image is shown in Figure 1 of Willett et al. 2013.

The Galaxy Zoo 2 (GZ2) project consists of 304,022

* This investigation has been made possible by the participation of more than 250,000 users in the Galaxy Zoo project. Their contributions are individually acknowledged at <http://authors.galaxyzoo.org>

¹ <http://zoo2.galaxyzoo.org/>

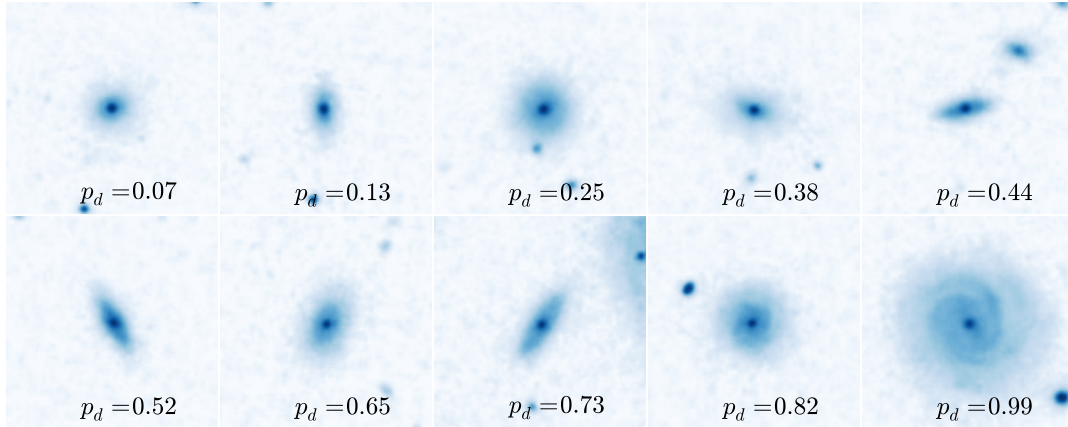


Figure 1. Randomly selected SDSS *gri* composite images from the sample of 1,299 Type 2 AGN showing the continuous probabilistic nature of the Galaxy Zoo sample from a redshift range $0.04 < z < 0.05$. The debiased ‘disc or featured’ vote fraction (see Willett et al. 2013) for each galaxy is shown. The scale for each image is 0.099 arcsec/pixel.

images from the SDSS DR8 (York et al. 2009; Aihara et al. 2011) a subset of those classified in Galaxy Zoo 1; GZ1) all classified by *at least* 17 independent users, with the mean number of classifications standing at ~ 42 .

Further to this, we required NUV photometry from the GALEX survey, within which $\sim 42\%$ of the GZ2 sample were observed, giving a total sample size of 126,316 galaxies. This will be referred to as the GZ2-GALEX sample.

The completeness of this sample is shown in Figure 2 of Smethurst et al. (2015) with the *u*-band absolute magnitude against redshift for this sample compared with the SDSS data set. Typical Milky Way L_* galaxies with $M_u \sim -20.5$ are still included in the GZ2 subsample out to the highest redshift of $z \sim 0.25$; however dwarf and lower mass galaxies are only detected at the lowest redshifts.

2.2 STARPY

STARPY 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 with the input of two observed photometric colours, a redshift, and the use of the SSP 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 therefore be described as:

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

where i_{sfr} is an initial constant star formation rate dependent on t_q (see 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 likelihood 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 run on the volume limited GZ2-GALEX sample ($0.01 < z < 0.25$).

2.3 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) which matched those in the GZ2-GALEX; we then required the $S/N > 3$ for each emission line as in Schawinski et al. (2010). Those galaxies which satisfy all of the inequalities defined in Kewley et al. (2001) and Kauffman et al. (2003b), giving 1,299 Type 2 AGN host galaxies ($\sim 9\%$ of the GZ2-GALEX sample). This will be referred to as the AGN-HOST sample.

This sample is shown in Figure 2 with those galaxies selected as Type 2 AGN marked in red and the rest of the GZ2-GALEX in black. All of the galaxies of the AGN-HOST sample was removed from the GZ2-GALEX sample along with any of those recently identified as Type 1 AGN by Oh et al. (2015) to produce a largely inactive sample of typical galaxies. These inactive galaxies are used as a control sample to the Type 2 AGN sample and will be referred to as the INACTIVE 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 that of 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 light from the AGN can be neglected

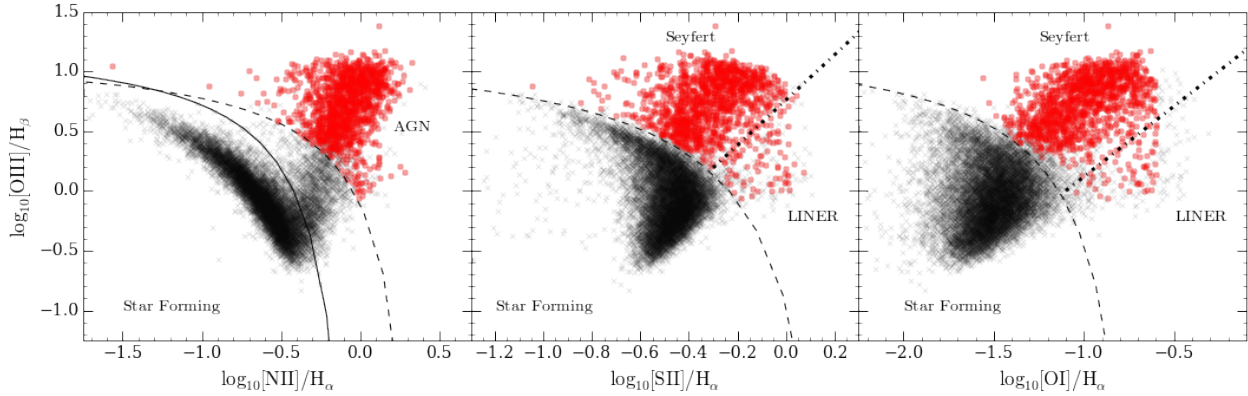


Figure 2. BPT diagrams for galaxies in the GZ2-GALEX sample with $S/N > 3$ for each emission line. The dashed lines show the inequalities defined in Kewley et al. (2001) to separate star forming galaxies from AGN; the solid line the inequality defined in Kauffman et al. (2003b) to separate star forming galaxies from composite SF-AGN galaxies; the dotted lines show the separation of LINERS and Seyferts from Kewley et al. (2006). Galaxies were selected for the Type 2 AGN sample if they satisfied all the inequalities from Kewley et al. (2001).

in comparison to that of the galaxy, however there is often some residual optical light that can affect the measurements of the host galaxy’s photometry. We can easily subtract this central optical AGN flux using the PSF magnitudes provided by SDSS, however the change in the colours of these galaxies after this correction is negligible $\Delta(u-r) \sim 0.09$. In order to reduce the amount of uncertainty that will progress into the SFH population likelihoods, we will not use these corrected optical colours in favour of reducing unnecessary complexity. We also split both the AGN-HOST and INACTIVE samples into low ($\log M_* < 10.25 M_\odot$), medium ($10.25 < \log M_* [M_\odot] < 10.75$) and high ($\log M_* > 10.75 M_\odot$) masses to control for any degeneracies.

3 RESULTS

Each galaxy was run through STARPY to obtain a 2D likelihood distribution across the $[t_q, \tau]$ parameter space. The individual likelihood distributions of each galaxy were combined across the three mass bins defined in Section 2.3 for the AGN-HOST and GZ2-GALEX galaxies. Here we utilise the GZ2 morphologies to weight by the vote fractions to combine across the different populations to produce smooth and disc dominated likelihood distributions. We stress that this portion is purely for visualisation purposes and is no longer a Bayesian method.

These 2D 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 1D normalised probability distribution across the given parameter is shown for smooth (red) and disc (blue) dominated galaxies split into the three mass bins; low (top), medium (middle) and high (bottom) mass galaxies for the AGN-HOST (left) and INACTIVE (right) samples. In Figure 4 the percentage likelihood 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 hosts (left panels) and inactive galaxies (right panels) for both parameters. For the inactive galaxies, the likelihood for quenching at later times decreases with increasing mass, whereas for the lower mass galaxies the quenching is roughly constant with time for both smooth and disc dominated populations (left panel Figure 3). This is observational evidence of downsizing across the generic galaxy population whereby stars in massive galaxies form first and subsequent star formation at later times is suppressed therefore there is no star formation to quench (Cowie et al. 1996; Thomas et al. 2010).

The distribution of likelihood for AGN host galaxies across the quenching time t_q parameter (left panels of Figure 3), is very obviously different from that of the inactive galaxies (right panels of Figure 3). Recent quenching is the most dominant history across all three mass bins, particularly for low mass galaxies. However, this effect is dampened in higher mass galaxies where quenching at earlier times also has significant likelihood.

The distribution of likelihoods for the rate of quenching, τ , in Figure 4, show once again the AGN host (left panels) and inactive (right panels) galaxy population distributions are vastly different. The likelihood for rapid quenching ($\tau < 1$ Gyr) increases for inactive galaxies of increasing mass (see percentage likelihoods in the left hand panels of Figure 4) and the likelihood for slow quenching ($\tau > 2$ Gyr) also increases for inactive disc galaxies with increasing mass.

However, the distribution of likelihood of the rate of quenching for the AGN host galaxies is in fact the opposite to that seen for inactive galaxies. The likelihood for rapid quenching decreases with increasing mass for both smooth and disc dominated populations, whereas for slow quenching rates the likelihood increases with increasing mass for the disc dominated population.

4 DISCUSSION

The vast differences between the distribution of likelihood for the AGN-HOST and INACTIVE galaxy populations reveals

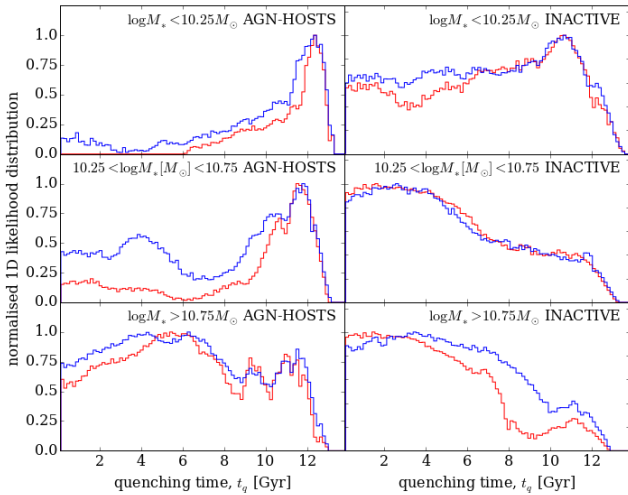


Figure 3. Likelihood distribution for the quenching time, t_q parameter, for AGN (left) host and inactive (right) galaxies, split into low (top), medium (middle) and high (bottom) mass galaxies for smooth (red) and disc (blue) galaxies. A low value of t_q corresponds to the early Universe and a high value to the recent Universe.

that AGN have a significant effect on the SFH of their host galaxy and can be associated with both recent rapid quenching and earlier, slower quenching histories.

As well as the clear evidence for downsizing in the inactive galaxy population in Figure 3, we can also see its effect on the AGN-HOST population. Although recent quenching is the dominant history, quenching at earlier times also has significant likelihood with increasing mass. These galaxies may have undergone downsizing earlier in life with the current AGN also having an effect on the SFR through feedback, causing a recent, rapid quench of any residual star formation.

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

If a slowly ‘dying’ or ‘dead’ galaxy has an infall of gas either through a minor merger, galaxy interaction or environmental change, this can trigger further star formation and feed the central black hole, igniting an AGN. In turn this AGN can then quench the recent boost in star formation. This track is similar to the evolution history theorised for blue ellipticals (Kaviraj et al. 2013; McIntosh et al. 2014; Haines et al. 2015). As for the disc galaxies, it also follows from the ideas of previously isolated discs evolving slowly by the Kennicutt-Schmidt (KS; Schmidt 1959; Kennicutt 1997)

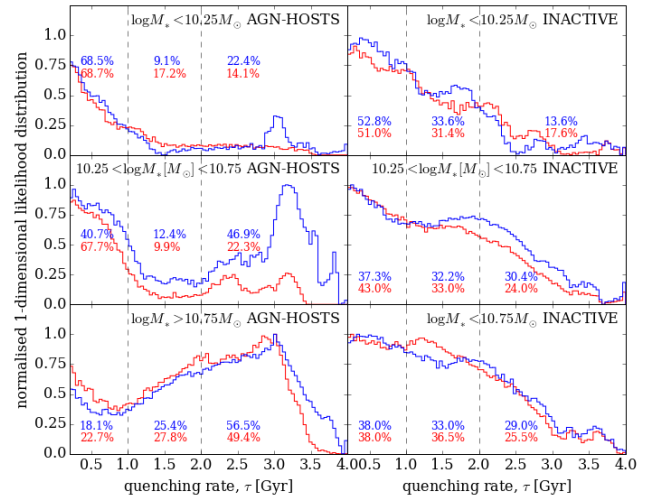


Figure 4. Likelihood distribution for the quenching rate, τ parameter, for AGN-HOST (left) host and INACTIVE (right) galaxies, split into low (top), medium (middle) and high (bottom) mass galaxies for smooth (red) and disc (blue) weighted populations. The dashed lines show the separation between rapid ($\tau < 1.0$ Gyr), intermediate ($1.0 < \tau < 2.0$) and slow ($\tau > 2.0$ Gyr) quenching timescales with the percentage of the likelihood distribution in each region for disc (blue) and smooth (red) populations shown. A small (large) value of τ corresponds to a rapid (slow) quenching rate.

law which can then undergo an interaction or merger to reinvigorate star formation and feed the central black hole.

The difference between the AGN host and inactive galaxies distribution of likelihood in Figure 4 for the rate of quenching, τ , tells a story of gas reservoirs. Smethurst et al. (2015) speculated that rapid quenching rates could be attributed to mergers of galaxies, therefore we expect the trend of increasing likelihood for rapid quenching rates with increasing mass for the inactive galaxies, as mergers 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). Similarly we also expect the trend of increasing likelihood for slow quenching rates with increasing mass as Smethurst et al. (2015) attributed slower quenching histories to secular (non-violent) evolution of isolated galaxies (Kormendy & Kennicutt 2004; Cisternas et al. 2011) which are often lower in mass (Varela et al. 2004; Bamford et al. 2009) due to their isolation from other galaxies and therefore any potential gas reservoirs.

The trends with likelihood of τ in Figure 4 are reversed however for the AGN host galaxies. The likelihood for rapid quenching decreases with increasing mass for both smooth and disc dominated populations and for slow quenching increases with increasing mass disc galaxies. It appears that the most massive disc galaxies, therefore with the most massive gas reservoirs evolve with a slow quench of star formation through the KS law and also have enough gas to feed the central black hole to trigger a current AGN (Varela et al. 2004; Emsellem et al. 2015). Conversely, a rapid quench, possibly caused by the AGN itself through negative feedback, is only the most dominant history for low mass 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). This rapid quenching is still apparent but at a lower likelihood across the smooth and disc populations in higher mass galaxies, which have larger potentials, making it more difficult for the AGN to have an impact on the galaxy wide SFR (Ishibashi et al. 2012; Zinn et al. 2013).

For the medium mass AGN-HOST population we see a bimodal distribution of likelihood between these two dominant quenching histories, challenging the typical merger driven theory for the co-evolution of black holes and their host galaxies.

We have used morphological classifications from the Galaxy Zoo 2 project to determine the morphology-dependent star formation histories of AGN host galaxies in comparison to a ‘typical’ inactive galaxy population via a Bayesian analysis of an exponentially declining star formation quenching model. We determined the most likely parameters for the quenching onset time, t_q and quenching timescale τ and find clear differences in the combined population likelihoods between inactive and AGN host galaxies. We find evidence for a link between a galaxy currently hosting an AGN and its SFR. We find evidence of downsizing in massive inactive galaxies, which appears as a secondary effect in AGN host galaxies with the dominant quenching occurring at recent times. Our main finding is the detection of the dominance of rapid, recent quenching across the population of AGN host galaxies.

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