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

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ABSTRACT

We present a population study of the star formation history (SFH) 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 to have undergone a recent and rapid drop in their star formation rate. This result is not seen for the 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 contrary to the 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 appears to be the key driver behind this co-evolution.*

1 INTRODUCTION

Two open issues in modern astrophysics are: (i) how do galaxies and their central black holes co-eveolve and (ii) what are the effects, if any, of AGN feedback. There is an obvious relationship between the mass of a central black hole and its host galaxy, commonly referred to as the Maggorian relationship (Magorrian et al. 1998; Marconi & Hunt 2003; Haring & Rix 2004). AGN feedback was first suggested 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 AGN 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 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 yet to be found.

Here we present a large observational population study of the quenching of the host galaxies of Type 2 AGN, using a new PYTHON routine, STARPY[1], which implements 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) 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?

The zero points of all magnitudes are in the AB system and where necessary we adopt the WMAP Seven-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] citizen science project

* 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://github.com/zooniverse/starpy`
[2] `http://zoo2.galaxyzoo.org/`

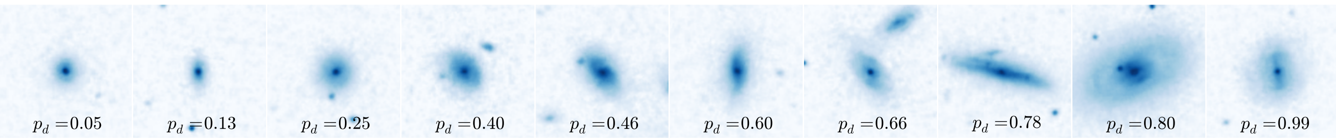

Figure 1. Randomly selected SDSS *gri* composite images from the sample of 1, 244 Type 2 AGN showing the continuous probabilistic nature of the Galaxy Zoo sample from a redshift range $0.04 < z < 0.05$. The debiased 'disc or featured' vote fraction (see Willett et al. 2013) for each galaxy is shown. The scale for each image is 0.099 arcsec/pixel.

(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 used 304, 022 images from the SDSS DR8 (York et al. 2009; Aihara et al. 2011) 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 were observed, giving a total sample size of 126, 316 galaxies ($0.01 < z < 0.25$). 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 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.

2.1 STARPY

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 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 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 run on the GZ2-GALEX sample.

2.2 AGN Sample

We select 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), Kauffman et al. (2003b) and Kewley et al. (2006) are selected as Type 2 AGN, giving 1, 244 host galaxies ($\sim 9\%$ of the GZ2-GALEX sample). Sarzi et al. (2010); Yan & Blanton (2012) and Singh et al. (2013) have all demonstrated that LINERs are not powered by AGN, therefore for purity, we exclude these galaxies from the sample (58 galaxies in total) with no change to the results. This will be referred to as the AGN-HOST sample.

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 rest of the GZ2-GALEX in black. For this sample the mean $\log L[OIII] \sim 45.0$ with a range of $\log L[OIII]$ luminosities of $42.9 - 46.7$.

All of the galaxies of the AGN-HOST sample are removed from the GZ2-GALEX sample along with any of those 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.

Since this investigation is focussed on whether an AGN can have an impact on the SF of their host galaxy, we must consider whether there is a selection effect present in this identification method. The possibility that an AGN in a host galaxy in the blue cloud could be obscured by the emission from star formation was addressed by Schawinski et al. (2010). They showed, through a simple empirical experiment which simulated the addition of an AGN of certain luminosity to a star forming galaxy, that this method produces a complete sample, even in the blue cloud, at luminosities of $L[OIII] > 10^{40} erg\ s^{-1}$. We can therefore assume that this method is producing a complete sample of AGN, fully sampling the range of star formation rates of their host galaxies.

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

[3] `http://github.com/zooniverse/starpy`

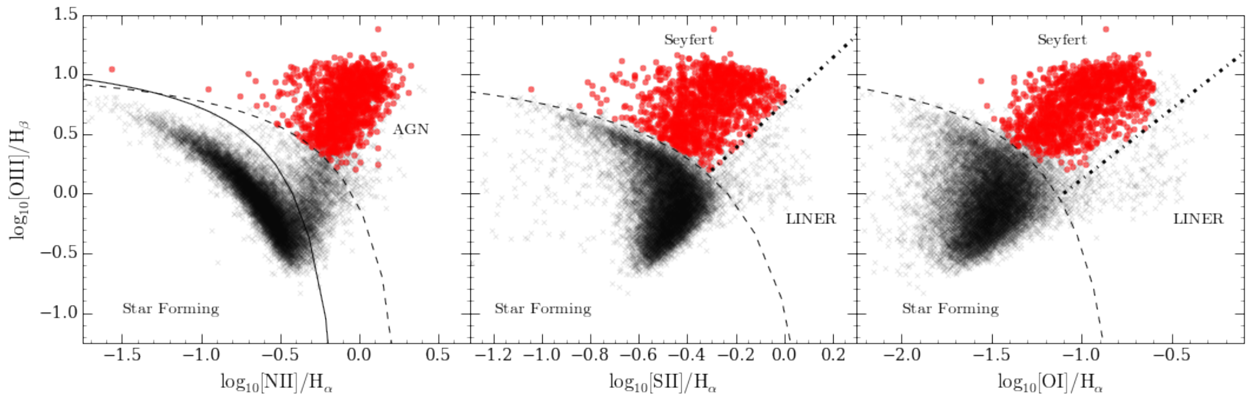

Figure 2. BPT diagrams for galaxies in the GZ2-GALEX sample (black crosses) with S/N > 3 for each emission line. Inequalities defined in: Kewley et al. (2001) to separate star forming galaxies from AGN (dashed lines), Kauffman et al. (2003b) to separate star forming from composite SF-AGN galaxies (solid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

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 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 with $\Delta(u-r) \sim 0.09$. 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, medium and high masses (see Table 1) to control for any degeneracies. Masses were calculated using the $u-r$ colour and absolute r-band magnitude with the method outlined in Baldry et al. (2006).

3 RESULTS

Each galaxy was run through STARPY to obtain a 2-dimensional 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 Secition 2.2 for the AGN-HOST and GZ2-GALEX galaxies. The numbers of galaxies in each of these mass bins for each population are provided in Table 1. 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 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

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
$\log M_* < 10.25 M_\odot$	163 (12.5%)	41197 (33.4%)
$10.25 < \log M_*[M_\odot] < 10.75$	653 (50.3%)	46428 (37.7%)
$\log M_* > 10.75 M_\odot$	483 (37.2%)	35618 (28.9%)

is shown for smooth and disc dominated galaxies across three mass bins for the AGN-HOST and INACTIVE 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-HOST and INACTIVE populations for both parameters. For the INACTIVE sample, the likelihood for quenching at later times decreases with increasing mass, until for the lower mass galaxies the quenching is roughly constant with time for both smooth and disc dominated populations (right panel Figure 3). This is observational evidence of downsizing across the generic galaxy population whereby stars in massive galaxies form first and quench early (Cowie et al. 1996; Thomas et al. 2010).

The distribution of likelihood for the AGN-HOST population across the quenching time t_q parameter (left panels of Figure 3), is obviously different from that of the inactive galaxies (right panels of Figure 3). Recent quenching is the 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 and INACTIVE population distributions are different. The likelihood for rapid quenching ($\tau < 1$ Gyr) increases for the INACTIVE population of increasing mass (see percentage likelihoods in the left hand panels of Figure 4) and the likelihood for slow

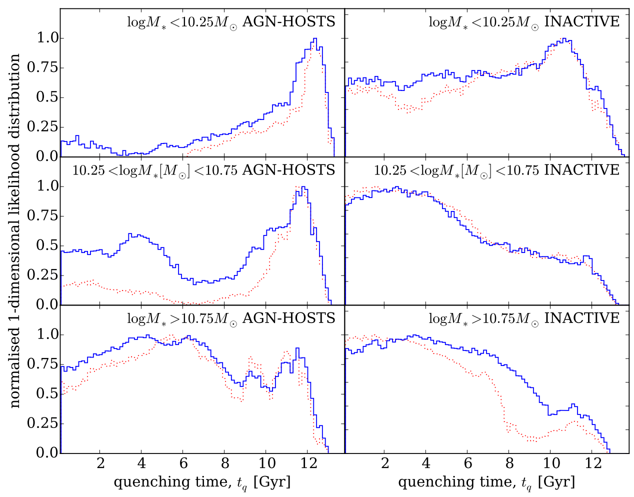

Figure 3. Likehood distribution for the quenching time, t_q parameter, for AGN (left) host and inactive (right) galaxies, split into low (top), medium (middle) and high (bottom) mass galaxies for smooth (red dashed) and disc (blue solid) galaxies. A low value of t_q corresponds to the early Universe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

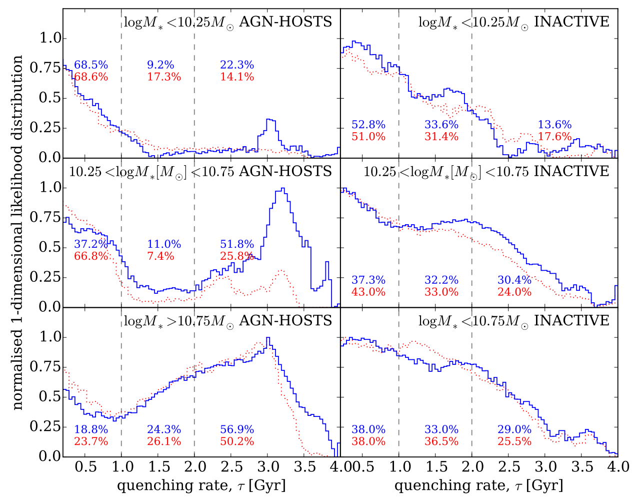

Figure 4. Likehood distribution for the quenching rate, τ parameter, for AGN-HOST (left) host and INACTIVE (right) galaxies, split into low (top), medium (middle) and high (bottom) mass galaxies for smooth (red dashed) and disc (blue solid) galaxies. The dashed lines show the separation between rapid ($\tau < 1.0$ Gyr), intermediate ($1.0 < \tau$ [Gyr] < 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.

quenching ($\tau > 2$ Gyr) also increases for the INACTIVE disc population with increasing mass.

However, the distribution of likelihood of the rate of quenching for the AGN-HOST population is opposite to that seen for INACTIVE population; the likelihood for rapid quenching decreases with increasing mass for both smooth and disc dominated galaxies. The likelihood distribution for the AGN-HOST galaxies shows evidence for the dominance of rapid, recent quenching having occurred across the entire population.

Interestingly, there is little difference between the two morphological types of AGN-HOST galaxies for either quenching parameter.

4 DISCUSSION

The differences between the distribution of likelihood for the AGN-HOST and INACTIVE galaxy populations reveals 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 evidence for downsizing in the INACTIVE population (Figure 3), we can also see its effect on the AGN-HOST population. Although recent quenching is the dominant history, quenching at earlier times has significant likelihood, increasing with mass. These galaxies may have been affected by 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) 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, 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 (calculated from the redshift and assuming all galaxies form at $t = 0$) is ~ 0.83 Gyr. This suggests 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. Smethurst et al. (2015) showed quenching is highly dependant on the morphology of the galaxy; since the AGN-HOST population does not show any morphological dependancies, this also suggests that this quenching is caused by AGN feedback.

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) 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 population distribution of likelihood in Figure 4 for the rate of quenching, τ, tells a story of gas reservoirs. Smethurst et al. (2015) speculate 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 population, 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).

The trends with likelihood of τ in Figure 4 are reversed however for the AGN-HOST population. The likelihood for rapid quenching decreases with increasing mass for both smooth and disc dominated populations. There is also more dominance of slower quenching timescales in the higher mass population across both morphologies. It appears that the most massive disc galaxies, 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). This challenges the typical merger driven theory for the co-evolution of black holes and their host galaxies.

Conversely, a rapid quench, possibly caused by the AGN itself through negative feedback, is 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, highlighting the strength of this method that it 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 AGN host galaxies in comparison to a 'typical' 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 quenching timescale τ and find clear differences in the combined population likelihoods between inactive and AGN host galaxies and for a link between 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 with higher masses. Our main finding is the detection of the dominance of rapid, recent quenching across a population of AGN host galaxies.

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