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Galaxy Zoo: Evidence for quenching caused by AGN feedback

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ABSTRACT

Evidence of recent quenching in galaxies with AGN. New Bayesian SFH tool STARPY lets us investigate the SFH as two parameters $[t, \tau]$ and investigate the 2D likelihood distribution in this space of active and inactive galactic nuclei host galaxies. We find that galaxies currently hosting an AGN have undergone very recent rapid quenching across all mass bins. This is not seen in those galaxies without current AGN. Downsizing, whilst apparent for the inactive galaxies is a secondary effect to that of theaGN impact on the SFH of active host galaxies particularly for lower mass galaxies. This suggests AGN are the cause/consequence of quenching. ⋆

1 INTRODUCTION

There is an observable obvious relationship between the evolution of a central black hole and it's host galaxy. The Magorrian relation shows this as do simulations.

This effect seems to be strongest during AGN phase of black hole growth (???).

It has been theorised that AGN can have 'negative feedback' on the star formation rate (SFR) of a galaxy. This is supported by the observational evidence that the largest fraction of AGN are found in green valley (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.

Here we find indirect observational evidence linking the star formation history (SFH) of a galaxy to the presence of a current AGN with the use of a novel new code implementing a Bayesian method, Given a NUV and an optical colour of an observed galaxy and by utilising SSP models, STARPYcan effectively model the SFH of a galaxy with two parameters.

Through this approach, we aim to determine the following:

(i) Are galaxies currently hosting an AGN undergoing quenching?
(ii) If so, at what rate does this quenching occur?
(iii) Are the AGN the cause or consequence of any quenching?

This letter proceeds as follows. Section 2 contains a description of the sample data, which is used in 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 of the results obtained. We also summarise our findings in Section 5. 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 2[1] 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 images from the SDSS DR8 (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. The completeness of this subsample of GZ2 matched to GALEX 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.

⋆ 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/`

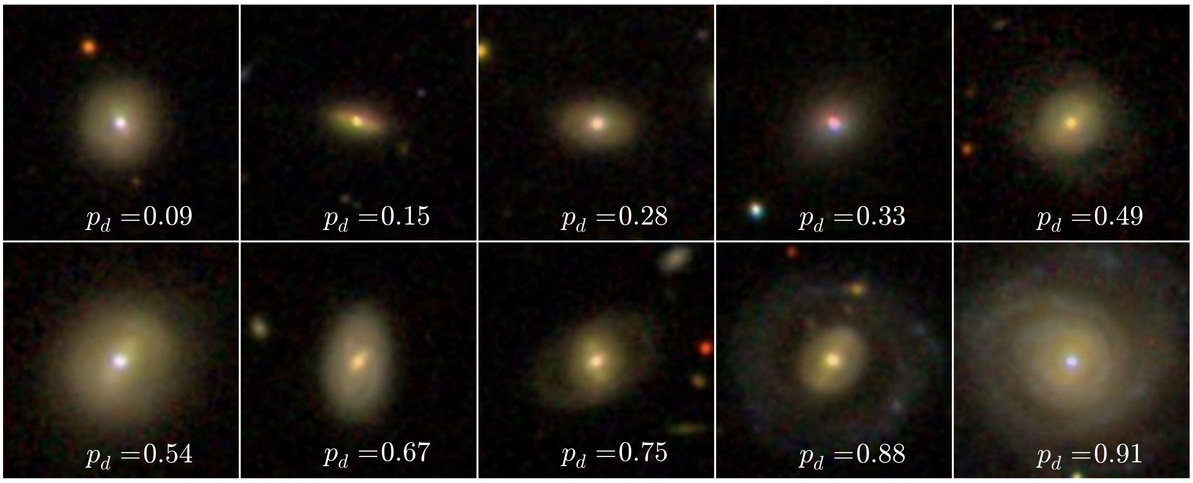

Figure 1. Randomly selected SDSS *gri* composite images from the sample of 984 Type 1 AGN showing the continuous probabilistic nature of the Galaxy Zoo sample from a redshift range $0.040 < z < 0.05$. The debiased 'disc or featured' vote fraction (see Willett et al. 2013) for each galaxy is shown. Note the bright point source of the AGN in the centre of each galaxy. The scale for each image is 0.099 arcsec/pixel.

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 **?**). A smaller τ value corresponds to a rapid quench, whereas a larger τ value corresponds to a slower quench. The output of STARPYis 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 a volume limited sample ($0.01 < z < 0.25$) of 126,316 galaxies of the Galaxy Zoo 2 project from SDSS DR8 (York et al. 2009; Aihara et al. 2011). This will be referred to as the GZ2-STARPY sample.

2.3 AGN Sample

We utilise a new sample of type 1 AGN selected by Oh et al. (2015) who built on the selection techniques of the OSSY catalogue[2] (Oh et al. 2011). To search for broad line region (BLR) AGN Oh et al. (2015) used a flux ratio between between two regions near the $H\alpha$ emission line in SDSS DR7 spectra. The two regions were $6460 - 6480\AA$ and $6523 - 6543\AA$ to give a flux ratio, F_{6533}/F_{6470}; which identified, if high, those candidate AGN host galaxies. Each spectra was fit using the IDL PPXF and GANDALF programs with the (Bruzual & Charlot 2003) and MILES stellar libraries using the Levenberg Marquardt minimisation method (Markwardt et al. 2009). From the measured continuums and emission line widths type 1 AGN were selected with the following criteria:

- $0.00 < z < 0.20$
- FWHM of $H\alpha > 800$ km s^{-1}
- A/N of broad $H\alpha > 3$

This resulted in a sample of 9,671 type 1 AGN identified by Oh et al. (2015) with broad line and luminosity measurements provided in the published catalogue. This sample was then matched to the GZ2-STARPY sample to give 984 galaxies currently hosting AGN.

As the optical and NUV photometry are used to predict the most likely star formation history model of these galaxies, the flux contribution from the AGN at the centre of each galaxy had to be removed from the overall petrosian flux to give only the stellar contribution. This becomes an obvious method when the bright central point sources of the AGN in each galaxy of Figure 1 are noted.

This was achieved using the petrosian and SF magnitudes provided by SDSS and the 'AUTO' and 'aperture 3' magnitudes provided by GALEX. The GALEX PSF size is quoted at $5 - 6''$ therefore in order to ensure that the entirety of the flux contribution from the AGN was removed the larger $7''$ 'aperture 3' was selected (as opposed to the

[2] http://gem.yonsei.ac.kr/ossy/

smaller 4.5″ 'aperture 2' provided by GALEX). These magnitudes were k-corrected to $z = 0$ with the routine provided in Chilingarian et al. (2010) and extinction corrected using the dust maps of Schlegel et al. (1998)[3] and optical and NUV $A/E(B-V)$ values from Schlafly & Finbeiner (2011) and Seibert et al. (2005) respectively.

This sample is studied in three different mass bins with 112 (11%) low mass ($M_* < 10.25\ M_\odot$), 572 (58%) medium mass ($10.25 < M_*[M_\odot] < 10.75$) and 300 (31%) high mass ($M_* > 10.75\ M_\odot$) galaxies and is compared to the larger GZ2-STARPY sample of 125,332 presumed inactive galaxies in the three different mass bins defined above, with 41,698 (33%) low mass, 47,391 (38%) medium mass and 36,243 (29%) high mass galaxies.

3 RESULTS

Each galaxy was run through STARPY to obtain the 2D likelihood across the $[t_q, \tau]$ parameter space. These individual likelihood distributions of each galaxy are combined across the three mass bins defined in Secition 2.3 for active and inactive nuclei host galaxies. We also utilise the GZ2 morphologies and weight by the vote fractions to split the sample as smooth and disc galaxies. We stress that this portion is purely for visualisation purposes and is no longer a Bayesian method. Figures 2 and 3 show these summed likelihood distributions across the parameter space for smooth and disc galaxies respectively across the three mass bins comparing AGN host galaxies and inactive galaxies.

4 DISCUSSION

Distinct difference between the distribution of likelihood for AGN and inactive galaxies. Peak at rapid, recent quenching times for AGN hosts as opposed to a drop in the likelihood at recent quenching times for inactive galaxies.

This is evident of downsizing - stars in massive galaxies form first and star formation at later times is suppressed, therefore minimal quenching occurs at later times because there is no SF to quench. Evident in most massive galaxies, both smooth and disc. Downsizing still apparent in the AGN hosting galaxies at higher masses, just also have extra "boost" of quenching occurring at the rapid, recent timescales. This is the dominant mechanism for low mass galaxies which is smeared out to due to the secondary effects of downsizing in higher mass galaxies.

Slow quenching is the most likely quenching track for disc galaxies, as shown by **?**. In inactive galaxies this likelihood increases with decreasing mass, however for galaxies currently hosting AGN likelihood increases for increasing mass.

Is the AGN the cause or consequence of quenching? Could argue both ways; (i) lack of likelihood of recent rapid quenching tracks for inactive galaxies suggests they are the cause but (ii) the shift of the peak of the time when the most quenching is occurring to later times for the active galaxies with increasing mass suggest a consequence ,otherwise the lifetime of the AGN is not long enough to be detected.

5 CONCLUSION

AGN and SFH linked. Rapid == high luminosity but there's not a lot of those. Slow == low luminosity and there's loads of those. Clear evidence for quenching driven by AGN - negative feedback.

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This publication made extensive use of the Tool for Operations on Catalogues And Tables (TOPCAT; Taylor 2005) which can be found at `http://www.star.bris.ac.uk/~mbt/topcat/`. Ages were calculated from the observed redshifts using the *cosmolopy* package provided in the Python module *astroPy*[4]; Robitaille et al. 2013). This research has also made use of NASA's ADS service and Cornell's ArXiv.

[3] Software for extracting the $E(B-V)$ values from the Schlegel et al. (1998) dust maps is available at `github.com/rjsmethurst/ebvpy`

[4] `http://www.astropy.org/`

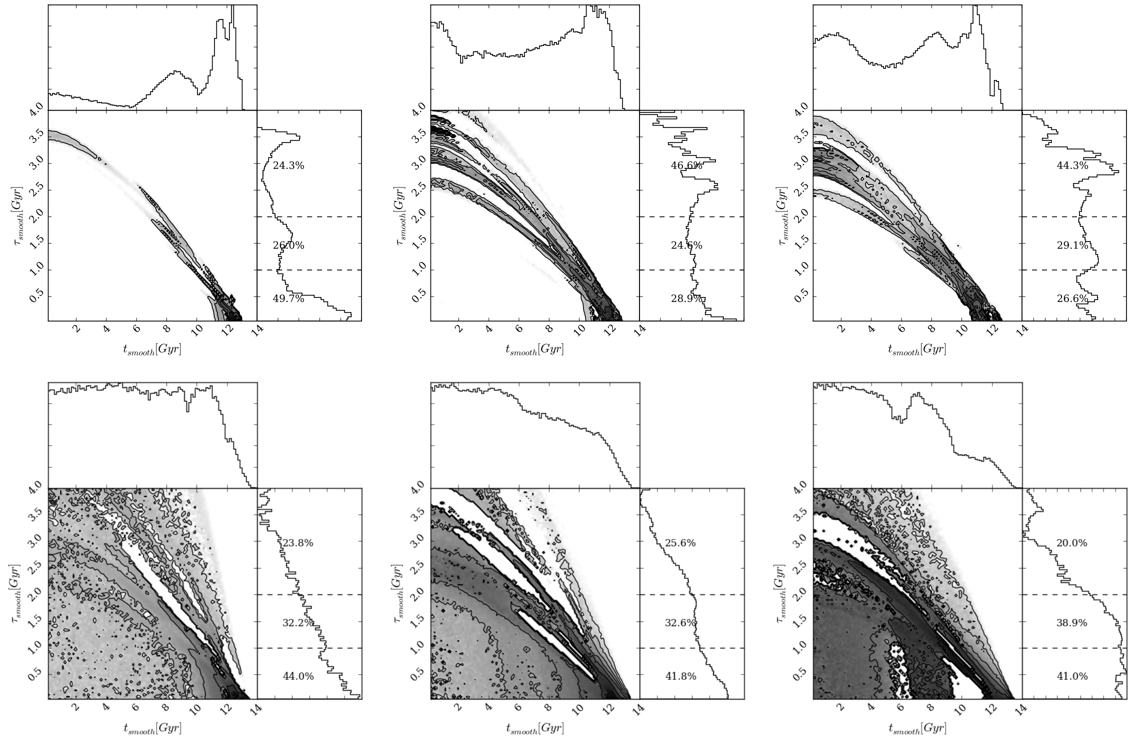

Figure 2. SLB plots for smooth AGN hosting galaxies (top) and smooth inactive galaxies (bottom). Split into low (left), medium (middle) and high (right) mass galaxies.

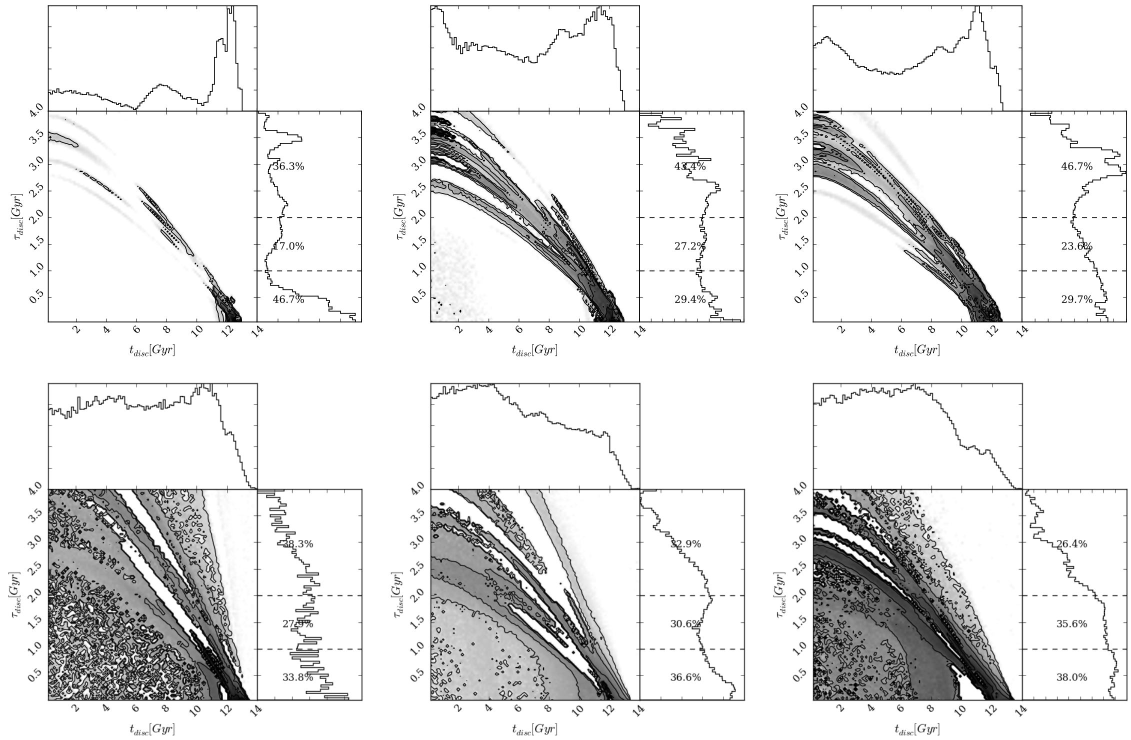

Figure 3. SLB plots for disc AGN hosting galaxies (top) and disc inactive galaxies (bottom). Split into low (left), medium (middle) and high (right) mass galaxies.

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