Galaxy Evolution and Feedback across Different Environments
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No evidence for quenching in quasars

Clare Wethers[1], **Nischal Acharya**,[1], **Roberto De Propris**[1], **Jari Kotilainen**[1,2], **Malte Schramm**[3] and **Andreas Schulze**[3]

[1]Finnish Centre for Astronomy with ESO (FINCA), Vesilinnantie 5, FI-20014 University of Turku, Finland
email: clare.wethers@utu.fi

[2]Department of Physics and Astronomy, Vesilinnantie 5, FI-20014 University of Turku, Finland

[3]National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan

Abstract. The role of quasar feedback in galaxy evolution remains poorly understood. Throughout this work, we explore the effects of negative feedback on star formation in quasar host galaxies, analysing two distinct populations of quasars. The first is a sample of high-redshift ($z > 2$) low-ionisation broad absorption line quasars (LoBALs) - a class of quasars hosting energetic mass outflows, in which we find evidence for prolific star formation ($>750 M_{\odot} yr^{-1}$) exceeding that of non-BAL quasars at the same redshift. The second is a population of 207 low-redshift ($z < 0.3$) quasars, in which we find an enhancement in the SFRs of quasar hosts compared to the underlying galaxy population, with no quasars residing in quiescent hosts over the last 2Gyr. Overall, we find no evidence for galaxy-wide quenching in either population, rather we suggest that the dominant effect of quasar activity is to enhance star formation in the galaxy.

Keywords. quasars: general, galaxies: general, galaxies: evolution, galaxies: active

1. Introduction

Understanding the interactions between quasars and their host galaxies is critical in building a coherent picture of galaxy evolution. In nearby galaxies tight correlations have been observed between the mass of the central super-massive black hole (M_{BH}) and that of the stellar bulge (e.g Kormendy & Ho 2013), leading to the idea that black holes and galaxies co-evolve. The mechanisms by which the black hole seemingly influences its host galaxy on scales beyond its sphere of influence remain poorly understood and as such, the origin of these tight correlations is still widely debated. Such observations are often explained by the presence of quasar feedback. Theoretical models predict quasar-driven outflows regulate black hole growth and star formation activity in the host by expelling gas from the galaxy which would otherwise fuel young stars and black hole accretion (e.g. Di Matteo *et al.* 2005; Fabian 2012; Carniani *et al.* 2016). In principle, this results in the quenching of star formation in the host. Perhaps the strongest evidence for this so-called *negative feedback* can be seen in the bright end of the galaxy luminosity function, where the number of bright galaxies is shown to decline more rapidly than models predict. Benson *et al.* (2003) for example demonstrate that basic cooling processes alone cannot account for this feature, finding instead that additional feedback processes are required. Indeed, observations have shown an anti-correlation between star formation in the host galaxy and the strength of quasar outflows (e.g. Farrah *et al.* 2010), indicating that these outflows act to suppress star formation in the host. On the other hand, semi-analytic models of galaxy assembly (Granato *et al.* 2004), invoke the same outflows to not only remove dense gas from the galaxy centre, but also to provide metal enrichment to the intergalactic medium (IGM). Such outflows may therefore also work to trigger regions of star formation in the galaxy by compressing cool, metal rich gas and allowing stars to form. Indeed, several studies have observed enhanced star formation in quasar hosts (e.g. Santini *et al.* 2012; Canalizo & Stockton 2001), implying that quasars may also act to enhance star formation in the galaxy via *positive feedback*. Understanding the interplay between negative and positive feedback mechanisms is important in building a comprehensive model of quasar-galaxy co-evolution. Here, we explore the impact of quasar feedback within two distinct quasar populations. The results presented are combined from a recent study on LoBALs at $z \sim 2$ (Wethers *et al.* 2020) and an ongoing study of low-z quasars in GAMA (De Propris *et al.* 2020, *in prep*)., both of which focus the impact of quasar feedback on star formation in galaxies.

2. Quasars at $z \sim 2$

Low-ionisation broad absorption line quasars (LoBALs) are an important, yet poorly understood subclass of quasars exhibiting direct evidence for energetic mass outflows. This makes them ideal laboratories in which to study the effects of quasar feedback. To this end, we make use of targeted *Herschel* SPIRE observations at 250, 350 and 500μm for a sample of 12 LoBALs at $2.0 < z < 2.5$ - a peak epoch of both black hole accretion and star formation. Full details of the LoBAL sample, data reduction and methodology can be found in Wethers *et al.* (2020), along with a more thorough analysis of the results outlined in this section.

2.1. *Detection rates*

Using signal-to-noise maps of our LoBAL sample, we find three of the 12 LoBALs (25 per cent) are detected at $>5\sigma$ in all SPIRE bands. If quasar outflows are responsible for quenching star formation in the galaxy, we would expect a general decrease in the FIR detection rate of LoBALs compared to non-BAL quasar populations containing no such outflows according to an evolutionary BAL interpretation (e.g. Boroson *et al.* 1992), assuming the FIR emission is correlated with the star formation in the galaxy. To this end, we compare the detection rate of our LoBAL sample to that for a sample of 100 non-BAL quasars outlined by Netzer *et al.* (2016), which are broadly matched to our LoBAL sample in terms of both redshift and luminosity (L_{bol}). After adjusting for the different detection limit of each sample, we find the FIR detection rate of LoBALs to be higher than that of non-BALs by a factor of $\sim$1.6. We therefore conclude an enhancement in the FIR detection rate of LoBALs compared to their non-BAL counterparts, implying that quasar outflows work to enhance star formation (and thus the FIR flux) in its host on short timescales, rather than quenching the galaxy, although we cannot rule out quenching on timescales longer than the LoBAL lifetime.

2.2. *FIR SFRs*

To confirm whether the enhancement seen in the detection rate of LoBALs is indeed associated with higher star formation rates (SFRs) in these systems, we compare the inferred SFR at the detection limit of our sample to another sample of 20 non-BAL quasars from Schulze *et al.* (2017), for which SFRs have been derived from their 850μm fluxes. As such, we take the nominal 5σ flux threshold for our sample at 250μm (25.4mJy) and fit a modified blackbody (or *greybody*) curve to this single photometry point. The fitted greybody curve is integrated over the FIR wavelengths (8-1000μm) to calculate the FIR luminosity, L_{FIR}, which is then converted to a SFR following the methods outlined in

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Table 1. The values and 1σ uncertainties of T_{DUST}, L_{FIR} and SFR inferred from the SED fitting for the sub-sample of detected LoBALs and for the stacked non-detections, where the 3σ upper limit on the SFR is instead given.

Name	T_{DUST} [K]	log L_{FIR} [ergs^{-1}]	SFR_{FIR} [$M_{\odot}yr^{-1}$]
SDSSJ0810+4806	$33.49^{+7.11}_{-5.70}$	$46.21^{+0.11}_{-0.12}$	740^{+220}_{-170}
SDSSJ0839+0454	$42.02^{+4.64}_{-4.32}$	$46.55^{+0.07}_{-0.08}$	1610^{+280}_{-260}
SDSSJ0943 -0100	$47.07^{+2.67}_{-2.50}$	$46.72^{+0.04}_{-0.04}$	2380^{+220}_{-210}
Stacked non-detections	$35.78^{+13.98}_{-7.06}$	$45.77^{+0.09}_{-0.11}$	<440

Kennicutt & Evans (2012). This returns a crude lower limit on the SFRs of our detected targets of $640M_{\odot}yr^{-1}$. Whilst three of the 12 LoBALs in our sample (25 per cent) are detected at $>5\sigma$ in all SPIRE bands, and thus lie above this lower SFR limit, just one target in Schulze *et al.* (2017) returns SFR$\,>640M_{\odot}yr^{-1}$, corresponding to 5 per cent of their sample. We therefore suggest that the enhancement we observe in the FIR detection rate of LoBALs, indicates an enhancement in the SFR of LoBALs compared to non-BAL quasars.

Having found evidence for enhanced star formation among LoBALs, we now seek to measure the individual SFRs for the three LoBALs in our sample detected at $>5\sigma$ in all *Herschel* SPIRE bands via SED fitting. To this end we combine the SPIRE photometry (250, 350 and 500μm) with additional photometry from *Herschel* PACS (70 and 100μm) and WISE (3.4, 4.6, 12.0 and 22.0μm). The full set of photometry (SPIRE + PACS + WISE) is fit with a two-component model, comprising a greybody template and a torus SED (Mor & Netzer 2012) to account for the potential contribution of quasar heating to the FIR emission. The fitting itself utilises a Markov-Chain Monte-Carlo (MCMC) method in order to obtain full posterior distributions on the best-fit model parameters and to marginalise over any nuisance parameters (Metropolis *et al.* 1953; Hastings 1970; Foreman-Mackey *et al.* 2013). Throughout the fitting we define three free parameters: the vertical scaling of both the torus SED (X_{TORUS}) and the greybody template (X_{SF}), and the dust temperature of the greybody template (T_{DUST}). Given the limited photometry tracing the cool dust emission, we adopt a fixed value of $\beta = 1.6$, consistent with the work of Priddey & McMahon (2001). Full details of the fitting routine can be found in Wethers *et al.* (2020). The SFR of each LoBAL is then estimated from the best-fit model by integrating over the FIR wavelengths (8-1000μm) of the greybody component. The resulting SFRs are presented in Tab. 1, along with the best-fit parameters derived from the fitting. The best-fit SEDs are also shown in Fig. 1. For each of the three detected LoBALs we derive high SFRs in the range 740-2380$M_{\odot}yr^{-1}$. These rates are consistent with the results of Pitchford *et al.* (2019), who find evidence for prolific star formation (SFR$\,\sim2000M_{\odot}yr^{-1}$) in an FeLoBAL - a class of LoBAL with additional iron absorption features in their spectra.

2.3. *Stacking the non-detections*

Despite finding evidence for prolific star formation within our LoBAL sample, we note that the majority of our sample (75 per cent) remain undetected in at least one of the *Herschel* SPIRE bands. A mean weighted stack of these undetected targets returns a 3σ upper limit on the SFR of $\lesssim440M_{\odot}yr^{-1}$. Even among the non-detected targets we therefore cannot rule our prolific star formation. As such, we find no evidence to suggest that LoBAL outflows act to instantaneously suppress star formation in their hosts. Rather, star formation in LoBALs appears enhanced relative to non-BALs, suggesting that outflows may trigger an increase in star formation. However, due to the poor sensitivity of

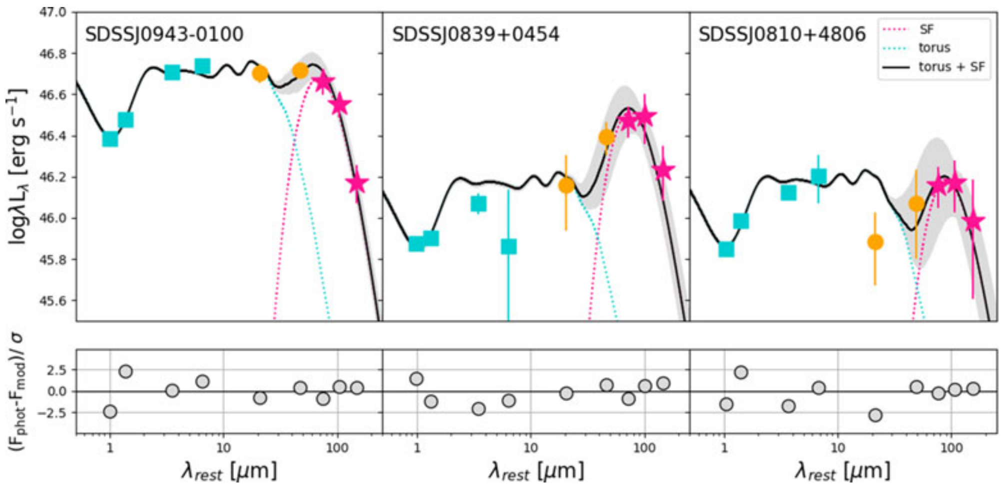

Figure 1. Figure taken from Wethers *et al.* (2020). **Upper:** Best-fit SED template based on the combined WISE (*blue squares*) + PACS (*orange circles*) + SPIRE (*pink stars*) photometry. The total model (*black*) is comprised of contributions from a hot torus (*dotted cyan*) and a star forming galaxy (*dotted pink*). Grey shaded regions denotes the 1σ uncertainty in the total model. Lower: Error weighted residuals of the best-fit model.

Herschel at $z > 2$, we cannot rule out the possibility of quenching in individual targets lying below our detection threshold. Furthermore, at these redshifts, we are unable to resolve the regions in which star formation is occurring, and so cannot rule out quenching within specific regions of the galaxy.

3. Quasars at $z < 0.3$

Having found no evidence that LoBAL quasars reside in quenched galaxies at $z > 2$, we now seek to test the impact of quasar feedback on star formation at low redshift. To this end, we make use of 207 confirmed quasars from the Large Quasar Astrometric Catalogue (LQAC-4) (Gattano *et al.* 2018) at redshifts $0.1 < z < 0.3$, overlapping the three equatorial fields (G09, G12 and G15) of the Galaxy and Mass Assembly survey (GAMA) - the redshifts and survey regions over which GAMA is most complete. Based on the mass and redshift distribution of these quasars, we select 100 realisations of N galaxies as a matched comparison sample, where $N = 207$: the number of quasars in our sample. One major advantage of using GAMA is the large amount of supplementary data available providing information on the SFRs, stellar masses and star formation histories (SFHs) of the catalogued galaxies (Liske *et al.* 2015). Based on this information, we compare the distribution of specific SFRs (sSFRs) within our quasar sample to that of the matched galaxy sample, finding higher sSFRs in quasars than in the underlying galaxy population. Furthermore, whilst a small fraction of the quasars in our sample reside in the so-called *green valley*, we find no evidence that any of our quasars reside in fully quiescent hosts. Furthermore, based on the SFH information provided by GAMA, we conclude that this apparent enhancement in SFR has occurred within the last 100Myr, whilst stellar populations older than ∼1Gyr appear largely indistinguishable from those of the matched inactive galaxies (Fig. 2). We therefore suggest that not only do the quasars in our sample reside in actively star-forming hosts, they also have not resided in quiescent galaxies at any point over the last 2Gyr.

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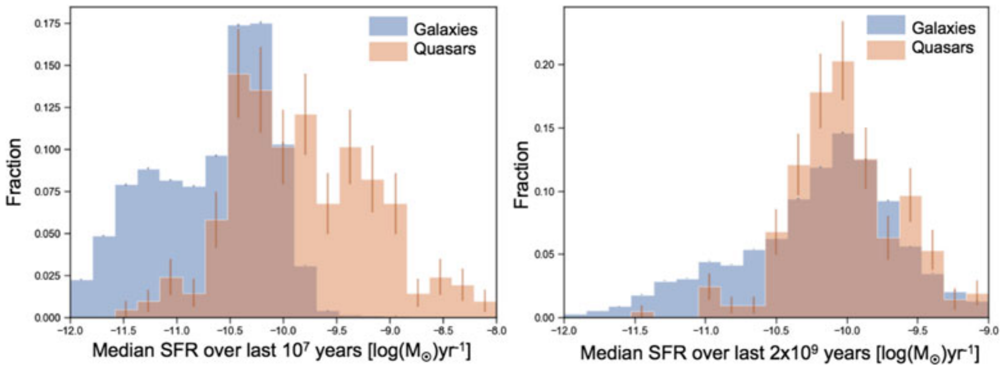

Figure 2. Figure adapted from De Propris *et al.* 2020, *in prep*. Median SFR averaged over 10Myr and 2Gyr for quasar host galaxies (*orange*) and the comparison sample of mass-matched inactive GAMA galaxies (*blue*).

4. Summary

Overall, we find no evidence for instantaneous galaxy-wide quenching either at $z > 2$ or at $z < 0.3$. Specifically, LoBALs at $z > 2$ exhibit higher SFRs than non-BALs, implying energetic mass outflows enhance star formation over short timescales. However, our results do not exclude quenching over longer timescales or galaxy-scale quenching in individual systems lying below our detection threshold. Similarly, we detect an enhancement in the SFRs of $z < 0.3$ quasars compared to the underlying galaxy population, finding no evidence for quasars existing in quiescent galaxies over the last 2Gyr. In future, spectra with high angular resolution will serve to resolve regions of quenching and active star formation in these quasars.

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Cristina Furlanetto Maximilien Franco

Clare Wethers

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Vincenzo Mainieri

Andrey Vayner

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