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The role of LoBALs in quasar evolution

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Abstract. Broad absorption line quasars (BALs) represent an interesting yet poorly understood population of quasars showing direct evidence for feedback processes via powerful outflows. Whilst an orientation model appears sufficient in explaining the sub-population of high-ionisation BALs (HiBALs), low-ionisation BALs (LoBALs) may instead represent an evolutionary phase, in which LoBALs exist in a short-lived phase following a merger-driven starburst. Throughout this work, we test this evolutionary picture of LoBALs by comparing the FIR detection rates, SFRs and environments for a sample of 12 LoBALs to other quasar populations at $2.0 < z < 2.5$, making use of archival *Herschel* SPIRE data. We find the LoBAL detection rate to exceed that of both HiBALs and non-BALs, indicating a potential enhancement in their SFRs. Indeed, we also find direct evidence for high SFRs ($>750\,M_{\odot}yr^{-1}$) within our sample which may be consistent with an evolutionary paradigm.

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

1. Introduction

Tight correlations have long been observed between the mass of super-massive black holes (M_{BH}) and various properties of their host galaxies (e.g. Magorrian *et al.* 1998; Kormendy & Ho 2013), yet the mechanisms by which these black holes seemingly shape regions of the galaxy beyond their sphere of influence remain poorly understood. For the most massive and luminous black holes (or *quasars*), it has been proposed that energetic mass outflows may be responsible for both quenching star formation in the galaxy and self-regulating black hole growth (e.g. Silk & Rees 1998; Di Matteo *et al.* 2005; Fabian 2012), but direct observations of galaxies hosting these outflows are sparse. Broad absorption line quasars (BALs) are an important class of quasars that show direct evidence of these mass outflows, likely launched as radiation-driven disc winds. They are thought to comprise anywhere between ∼15 (e.g. Hewett & Foltz 2003; Gibson *et al.* 2009) and ∼40 per cent (Allen *et al.* 2011) of the total quasar population and are generally classified into two types: high-ionisation BALs (HiBALs) and low-ionisation BALs (LoBALs). HiBALs make up ∼85 per cent of BALs and denote those objects containing only high-ionisation absorption features in their spectra, whereas LoBALs - accounting for the remaining ∼15 per cent of BALs - contain both high- and low-ionisation lines in their spectra.

In general, the BAL population remains poorly understood and the nature of BALs is still widely debated throughout the literature. To date, two main interpretations of the BAL phenomenon exist: orientation and evolution. In the orientation scenario, BALs are said to exist in most (if not all) quasars, but can only be viewed as such along specific sight-lines due to the high covering factor of the broad absorption line region. This model is not only consistent with a unified model of quasars, but also explains the similarities between the spectra of HiBALs and non-BALs (e.g. Weymann *et al.* 1991; Reichard *et al.* 2003) and the lack of enhancement in the millimetre detection rates of HiBALs (e.g. Priddey *et al.* 2007; Willott *et al.* 2003; Lewis *et al.* 2003), making it a popular model for the BAL phenomenon among HiBALs. On the other hand, BALs have been observed at a wide range of inclinations (Ogle *et al.* 1999; Di Pompeo *et al.* 2011), which directly contradicts this orientation scenario. However, this observation is consistent with an evolutionary interpretation of BALs, in which BALs - particularly LoBALs - exist in a short-lived transition period between a merger-induced starburst galaxy and an UV-luminous (non-BAL) quasar (e.g. Boroson & Meyers 1992). A key prediction of this scenario is the enhancement of star formation in LoBALs. Indeed, Canalizo & Stockton 2001 find evidence for this among LoBALs at $z < 0.4$, in which star formation also appears directly linked with tidal interactions in the galaxy. At higher redshifts however, Schulze *et al.* 2017 find no statistical differences in the distributions of either M_{BH} or Eddington ratios of LoBALs at $z \sim 2.0$ compared to a matched sample of non-BAL quasars, implying that LoBALs do not comprise a distinct population of objects. It remains to be seen however, whether these LoBALs exhibit a similar enhancement in star formation to their low redshift counterparts (Canalizo *et al.* 2001).

Here, we seek to directly test the evolutionary picture of LoBALs by answering the following questions. Firstly, do we see an enhancement in the FIR detection rate of LoBALs compared to populations of HiBALs and non-BALs? Secondly, is there evidence for prolific star formation in LoBALs consistent with a remnant starburst? And finally, do LoBALs exist in overdense environments, in which we may expect more frequent galaxy-galaxy interactions? The work presented here is a summary based on an ongoing project exploring the nature of LoBALs at $z > 2$. Full details of the LoBAL sample, data reduction and methodology can therefore be found in Wethers *et al.* 2019, *submitted*, along with a more thorough analysis of the results outlined here.

2. FIR Detection Rates

One prediction of the LoBAL evolutionary paradigm is the enhancement in the detection rate of LoBALs with regards to other quasar populations. If LoBALs mark a post-starburst phase in the lifetime of a quasar, we would expect them to appear bright at FIR wavelengths tracing the peak of the cool dust emission from star formation. As such, the FIR detection rates of LoBALs are expected to be higher than for populations of both HiBALs and non-BAL quasars, neither of which are typically associated with starburst activity in the galaxy. To this end, we make use of targeted *Herschel* SPIRE imaging at 250, 350 and 500 μm for 12 LoBALs at $2.0 < z < 2.5$. The initial selection criteria for this sample is outlined in Schulze *et al.* 2017, with full details of the observations used given in Wethers *et al.* 2019, *submitted*. We compare the detection rate of our LoBAL sample to a population 49 HiBALs at similar redshifts (Cao Orjales *et al.* 2012). In each case, we classify a detection as a source appearing in every band with a flux greater than the nominal 5σ limits outlined in Cao Orjales *et al.* 2012 (>33.5 mJy at 250 μm; >37.7mJy at 350 μm; >44.0mJy at 500 μm). Fig. 1 shows the fraction of LoBALs detected in all SPIRE bands compared to the corresponding HiBAL fraction, from which the detection rate of LoBALs is found to be a factor of ~8.5 greater than that of HiBALs. Similarly, we compare the detection rate of our sample to a sample of non-BALs outlined in Netzer *et al.* 2016 based on their nominal detection thresholds of >17.4, >18.9 and >20.4 mJy at 250, 350 and 500 μm respectively (Fig. 1). Again, we find evidence for an enhancement in the FIR detection rate of LoBALs by a factor of ~1.6.

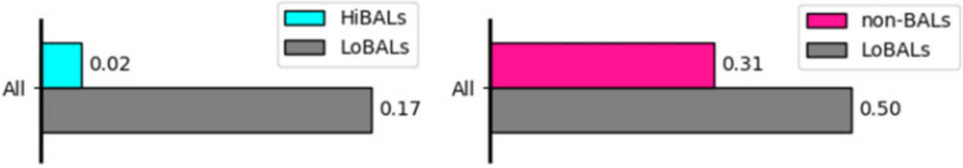

Figure 1. Figure adapted from Wethers *et al.* 2019. *Left:* FIR detection rate of our LoBAL sample compared to that of the HiBAL sample in Cao Orjales *et al.* 2012. *Right:* LoBAL detection rates compared to that of the non-BAL quasar sample in Netzer *et al.* 2016.

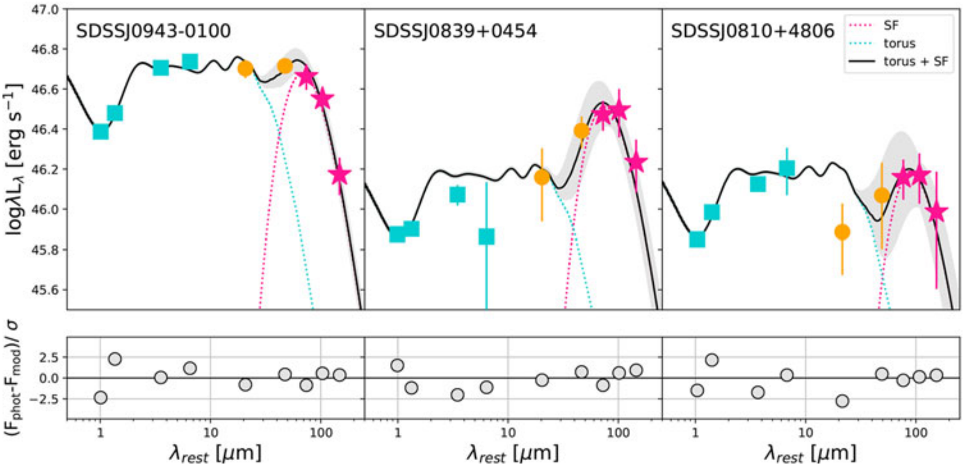

Figure 2. Figure from Wethers *et al.* 2019. *Upper:* Best-fit SED template based on the combined WISE (*blue squares*) + PACS (*orange circles*) + SPIRE (*pink stars*) photometry. The total model (*black solid line*) is comprised of contributions from a hot torus (*cyan dotted line*) and a star forming galaxy (*pink dotted line*). *Lower:* Error weighted residuals of the best-fit model.

3. LoBAL SFRs

Another key prediction of the LoBAL evolutionary paradigm is the enhancement in LoBAL SFRs. Of the 12 LoBALs in our sample, three are detected at $>5\sigma$ in all SPIRE bands, tracing the peak of the cold dust emission at $2.0<z<2.5$. Here, we present the SED fitting for the photometry of these three detected targets, from which we derive SFR estimates. We note that although any emission caused by quasar heating is thought to rapidly drop off at FIR wavelengths, some studies suggest that emission from hot dust in the torus may still contribute significantly in the *Herschel* SPIRE bands, particularly when considering bright quasars (e.g. Symeonidis *et al.* 2016). To this end, we therefore combine the *Herschel* SPIRE observations for our LoBAL sample with NIR photometry from both the Wide-field Infrared Survey Explorer (WISE) and *Hershel* PACS to estimate the effects of the potential quasar heating to the inferred SFRs. We simultaneously fit this combined photometry with two models: a template accounting for the expected quasar contribution (Mor & Netzer 2012) and a modified black body (or *greybody*) denoting the star forming component of the model. Fig. 2 shows the results of the SED-fitting, from which we find the quasar contamination at $\lambda>250\,\mu$m to be negligible for all of the detected LoBAL targets, accounting for <10 per cent of the total flux in the *Herschel* SPIRE bands.

To estimate the SFRs, we integrate over the FIR region (8-1000μm rest frame) of the star-forming component in the best-fit model to get the FIR luminosity (L_{FIR}) and convert this to a SFR based on the relation outlined in Kennicutt & Evans 2012. i.e. SFR

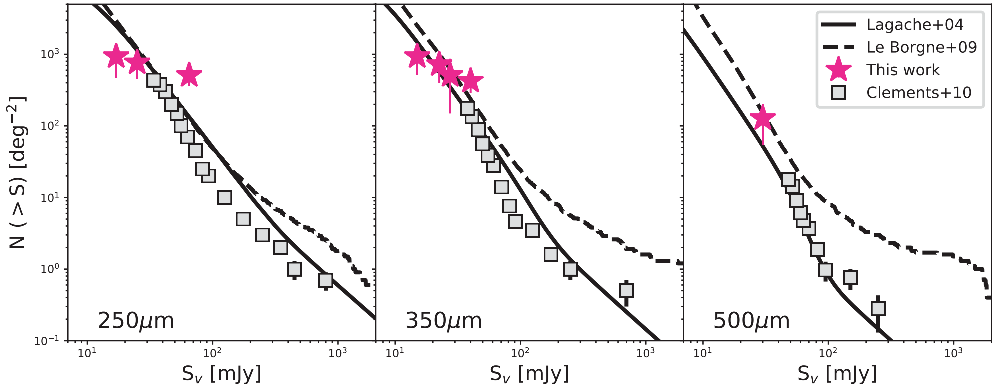

Figure 3. Figure from (Wethers *et al.* 2019, *submitted*). Number counts for the $>5\sigma$ detections within 1.5 arcmin of our LoBAL targets compared to those of the H-ATLAS field given in Clements *et al.* 2010 (*grey squares*). Model predictions from Lagache *et al.* 2004 (*solid line*) and Le Borgne *et al.* 2009 (*dashed line*) are included for reference.

$= 4.5 \times 10^{-44} \times \mathrm{L_{FIR}}$. Based on this relation, we derive SFRs of 740^{+220}_{-170}, 1610^{+280}_{-260} and 2380^{+220}_{-210} $\mathrm{M_\odot yr^{-1}}$ for the three detected LoBALs in our sample, providing evidence for prolific star formation in LoBALs. To determine whether this phenomenon is applicable to the full LoBAL sample (not just the detections), we create a mean-weighted stack of the remaining undetected LoBALs and fit the stacked photometry with a greybody template. Again, we integrate over the FIR component of the model and estimate the SFR, deriving a 3σ upper limit on the SFR for the non-detected LoBALs of $< 440\,\mathrm{M_\odot yr^{-1}}$. Even in cases where our targets are not detected by *Herschel*, we therefore cannot rule out moderate to high levels of star formation in LoBALs, proving consistent with the predictions of an evolutionary scenario, in which these systems succeed starburst activity in the host.

4. LoBAL Environments

The final test of the LoBAL evolutionary paradigm employed here is to look for overdensities on the local environments of LoBALs, which may be conducive to frequent galaxy-galaxy interactions. As such, we compare the number of sources detected within 1.5arcmin of our LoBAL targets - corresponding to $\sim$1 Mpc at $z \sim 2$ - to the blank field counts from the *Herschel* Astrophysical Tera-herz Large-Area Survey (H-ATLAS) in each of the SPIRE bands (Clements *et al.* 2010). Serendipitous sources in the image are required to lie above $>5\sigma$ and fluxes for each are measured within apertures of 22 arsec (250 μm), 30 arcsec (350 μm) and 40 arcsec (500 μm). Fig. 3 shows the number counts of sources within a 1.5 arcmin projected distance from our LoBAL targets compared to the galaxy number counts of the H-ATLAS fields. All number counts have been normalised to an area of 1.0 deg^2. From Fig. 3, we find no difference in the local ($\sim$1 Mpc) environments of LoBALs compared to the the H-ATLAS field and thus conclude that LoBALs do not exist in a special environment, but rather that their FIR environments are entirely consistent with the general galaxy population at $2.0 < z < 2.5$.

5. Summary

Overall, we find tentative evidence that LoBALs may exist in a distinct evolutionary phase, but cannot rule out an orientation scenario. On the one hand, we find evidence for an enhancement in the FIR detection rate of LoBALs compared to populations of both HiBAL and non-BAL quasars, indicating a likely enhancement in the SFRs in LoBALs. Indeed, SED fitting returns prolific SFRs ($>750\,\mathrm{M_\odot yr^{-1}}$) for the sample of LoBALs detected with *Herschel* SPIRE and similarly high SFRs ($\sim$440 $\mathrm{M}_\odot \mathrm{yr}^{-1}$) cannot be ruled out for the undetected sample. This observed enhancement in the SFRs of LoBALs directly supports one of the key predictions of an evolutionary explanation for the LoBAL phenomenon. On the other hand, we find no evidence that LoBAls exist in any kind of special environment. We find no statistical differences between the FIR environment of our targets compared to the H-ATLAS blank fields in any of the SPIRE bands and thus conclude LoBALs to reside in environments typical of the general galaxy population at $2.0 < z < 2.5$, potentially favouring an orientation interpretation of LoBALs.

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