The Co-Evolution of Galaxies and Quasars

My research primarily explores **the role of quasar feedback in galaxy formation**. As a post-doctoral research fellow at the University of Turku, I have worked on characterising the host galaxies of quasars across **multiple wavelengths**, placing particular focus on their **star formation rates (SFRs) and environments**. My main motivation is to understand the **interactions between quasars and their hosts** which will ultimately allow us to better constrain models of **galaxy evolution**. Throughout my postdoc and PhD I have worked within two **large collaborations** (DES and GAMA) and have experience in both observing and reducing **spectroscopic data**.

Heavily dust-reddened quasars in the UV

Current evolutionary models of the most massive galaxies predict the existence of a dust-obscured quasar phase following an active starburst, occurring as quasar-driven winds expel remnant dust and gas outwards from the central regions of the galaxy (Sanders et al., 1988; Hopkins et al., 2006). This so-called *blowout* phase is not yet well understood, with multiple groups identifying several seemingly distinct dust-obscured quasar populations (e.g. Eisenhardt et al., 2012; Assef et al., 2015; Ross et al., 2015). Much of my research focuses on characterising populations of these obscured quasars at $z{\sim}2$ - a peak epoch in both star formation and black hole accretion. During my Ph.D (2014-2018) I led the first population study of quasar hosts at $z{\sim}2$ in the restframe ultraviolet (UV) as part of the Dark Energy Survey (DES) collaboration. By exploiting dust obscuration towards the quasar I was able to separate the quasar light from that of the star-forming host galaxy in a sample of 17 luminous obscured quasars (Banerji et al., 2012, 2015), finding them to reside in prodigiously star-forming hosts, with the most actively star-forming galaxies appearing to host the most luminous quasars (Wethers et al., 2018). In several cases however, we were unable to distinguish between star formation and scattered Lyα from the quasar as the source of the restframe UV emission. Without a reliable measurement of the ongoing star formation in these systems, we are unable to make meaningful statements on the importance of such obscured quasar phase(s) in galaxy evolution. As such, I am currently leading a spectroscopic program with the Robert Stobie Spectrograph (RSS) on the South African Large Telescope (SALT) to confirm the source of this emission. This program will provide the first spectroscopic UV observations for this population of reddened quasars, with a vision to use the C_{IV}/He_{II} and C_{IV}/C_{III} line ratios to distinguish between starlight and scattered quasar continuum. Already, I have begun reducing the spectra for many of the targets in our sample, with much of my ongoing work focusing on the spectral analysis and organisation of follow-up observations where needed.

Heavily dust-reddened quasars in the Sub-mm

The rest-frame UV wavelengths however trace only the unobscured component of the star formation in luminous obscured quasar hosts - potentially accounting for a small fraction of the total. Observations at longer submillimetre (sub-mm) wavelengths trace the cool dust emission dominated by starlight and therefore offer the opportunity to study the obscured components of star formation in these systems (e.g. Banerji et al. 2014, 2017). In 2017 we were awarded 21.5 hours with SCUBA2 on the James Clerk Maxwell Telescope (JCMT) to follow up a sample of 20 luminous obscured quasars (Banerji et al., 2012, 2015), five of which directly overlap the sample in (Wethers et al., 2018). Towards the end of my Ph.D and during the early part of my postdoc, I reduced the raw data from these observations, utilising the ORAC-DR SCUBA2 data reduction pipeline to create source maps at 850μm. SFR estimates based on the 850μm fluxes, again reveal prolific star formation in the hosts of luminous obscured quasars. Furthermore, we find the detection rate of luminous obscured quasars to be higher that that of both UV-luminous quasars and the more heavily reddened population of hot dust obscured galaxies (HotDOGs) (Wethers et al., 2020).

Testing the evolutionary paradigm of LoBALs

One important class of dust-obscured quasars are low-ionisation broad absorption line quasars (LoBALs), which show direct evidence for energetic mass outflows. Throughout my postdoc, I have sought to test the evolutionary interpretation of LoBALs, in which these systems exist in the aforementioned *blowout* phase following a merger-induced starburst. In particular, my research looks for enhancements in the star formation rates (SFRs) of LoBALs potentially associated with starburst activity in the galaxy, along with overdensities in the local environments of LoBALs in which galaxy interactions may occur more frequently. Using the *Herschel* Interactive Processing Environment (HIPE), I processed archival observations overlapping a targeted program with the Spectral and Photometric Imaging Receiver (SPIRE) and the Photodetector Array Camera and Spectrometer (PACS) to derive aperture photometry for 12 LoBALs at 2.0<z<2.5. At these redshifts, *Herschel* traces the peak of thermal emission caused by heating of dust from star formation. By combining the *Herschel* photometry with archival data from the Wide-field Infra-red Survey Explorer (WISE), I modelled the LoBAL sample with a combination of templates and estimated the SFRs of our LoBAL sample (Fig.1), finding evidence for prolific star formation in the sample ($> 750\ M_\odot yr^{-1}$).

As part of this project, we were also awarded 16 hours with NOTCam on the Nordic Optical Telescope (NOT) to follow up several of our LoBAL targets with NIR spectroscopy, from which we measured the black hole masses based on the Hα line width. This allowed us to make direct mass-matched comparisons between the SFRs of our LoBAL sample and other quasar populations. We found evidence for enhanced star formation in LoBALs compared to populations of both high-ionisation BALs (HiBALs) (Cao Orjales et al., 2012) and non-BAL quasars (Netzer et al., 2016) at z$\sim$2-2.5, tentatively supporting the evolutionary LoBAL paradigm (Wethers et al.*submitted*). In terms of environment however, we find no evidence to support such an evolutionary picture. Despite finding several serendipitous sources (>5σ) within 1.5 arcmin (projected) of the LoBAL targets, the number counts of these sources are found to be entirely consistent with the blank field (Clements et al., 2010). We thus conclude LoBALs to reside in IR environments similar to typical galaxies at z$\sim$2-2.5.

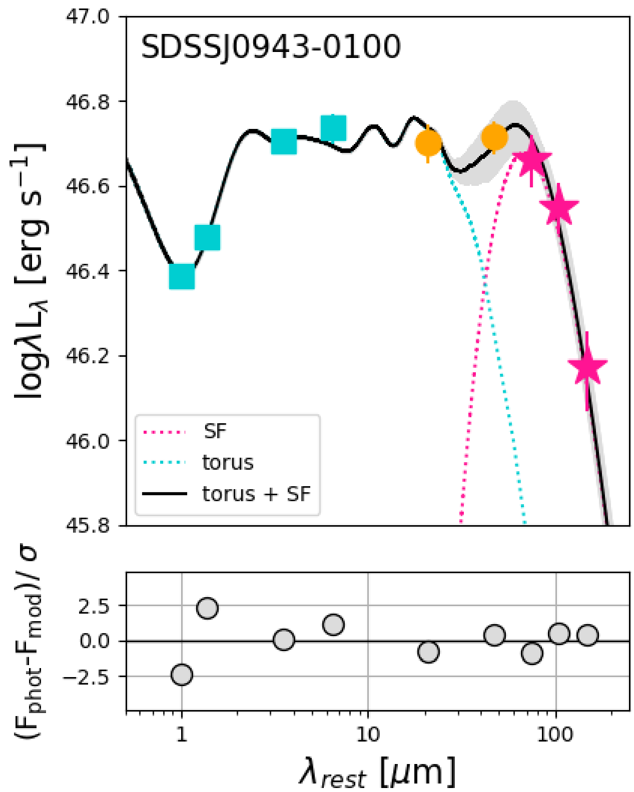

Figure 1: Model fitting for one of the LoBAL targets detected at >5 in all Herschel bands. ***Upper:*** Best-fit template based on the combined WISE (*blue squares*) + PACS (*orange circles*) + SPIRE (*pink stars*) photometry. The total model (*black solid line*) is comprised of contributions from a hot torus (*cyan dotted line*) and a star forming (SF) galaxy (*pink dotted line*). ***Lower:*** Error weighted residuals of the best-fit model.

The environments of low-redshift quasars

Despite finding evidence for enhanced star formation in the most luminous quasar hosts at z$\sim$2, there appears to be no connection between black hole accretion rate and star formation in the galaxy at lower redshifts (Urrutia et al., 2012) or among lower luminosity quasars (or AGN) (Jahnke et al., 2004). Understanding the evolution of quasars across different redshifts is therefore important in building a complete picture of galaxy evolution. To this end, I have been keen to expand my research to lower redshifts throughout my postdoc and have consequently become involved in two projects with the Galaxy and Mass Assembly (GAMA) collaboration, characterising both the star formation and environments of optically selected z<0.3 quasars in GAMA. Whilst initial results show quasars exhibit higher SFRs than typical mass-matched galaxies at this redshift (De Propris et al. *in collaboration review*), we find no difference in the preferred environments of the two populations (Fig.2), with both quasars and non-active galaxies seemingly preferring to reside in intermediate-density sheet and filament regions (Wethers et al. *in collaboration review*). In addition to finding no difference in the large-scale environments of the two populations, we find the two samples are consistent in terms of their group fraction, cylinder counts and surface densities. Moving forward, I am eager to build on this study, using the wealth of information in GAMA to look at the 3D environments of these quasars.

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