Infrared Diagnostics of Quasar Mode Feedback

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ABSTRACT

Quasar mode AGN feedback is a popular concept in cosmological models to explain the observed galaxy mass function, but observational evidence for this idea remains controversial. We review recent results from *Herschel* and *Spitzer* that provide strong evidence that quasar mode feedback can have a profound impact on AGN host galaxies, and that much of this impact happens while the AGN is still obscured. Holistic studies of quasar mode feedback thus require observations that span a wide wavelength range; in the far-infrared early on in the feedback phase, through to the optical/UV near the end of the feedback phase. We review how *SPICA* can contribute to this effort, by tracking quasar mode feedback across a wide range in obscuration levels.

1. INTRODUCTION

'Quasar' mode AGN feedback is the idea that a central SMBH exerts influence on short ($\sim 10^{7-8}$ yr) timescales and large (~kpc) spatial scales to quench star formation in its host galaxy. It is thought to occur when radiation from the accretion disk drives a wind of partially ionized gas into the host, which then empties the galaxy of fuel for star formation by kinetically driving the ISM gas out of the galaxy, and/or heating the ISM so it cannot collapse to form stars.

There is strong theoretical motivation for quasar mode feedback from models that trace the assembly of galaxies with redshift. Models without quasar mode feedback have difficulty in reproducing the observed redshift evolution of the galaxy mass function (e.g. Benson et al. 2003) whereas models with it show dramatic improvements in their consistency with observations (e.g. Somerville et al. 2008). Moreover, simulations of individual galaxies suggest that quasar mode feedback has a profound influence (e.g. Di Matteo et al. 2005; Debuhr et al. 2012; Choi et al. 2012). Observationally, quasar mode feedback has been inferred indirectly from e.g. the properties of molecular outflows in IR-luminous galaxies (Chung et al. 2011), and from the presence of winds with high kinetic fluxes in BAL QSOs (Moe et al. 2009), though some recent claims for quasar driven suppression of star formation (Page et al. 2012) are controversial (Harrison et al. 2012).

Overall however, the observational evidence for quasar mode feedback is weaker than theoretical evidence. We do not yet have a holistic observational picture for how quasar mode feedback impacts its host galaxy as a function of time. Primarily this is for three reasons. First, quantifying the impact of an AGN wind on its host galaxy, via e.g. the momentum injected into the galaxy ISM, is extremely difficult. Second, much of the most active periods of AGN growth, particularly in mergers, occur while the system is at least moderately obscured, making observations in the infrared essential. Third, uncertainties in our understanding of the evolution of IR-luminous systems mean it is not yet clear whether obscured mergers are invariably the antecedents of classical QSOs.

2. OBSERVATIONAL EVIDENCE FOR AGN FEEDBACK

Recently, there have been several important observational advances in our understanding of possible AGN feedback mechanisms. We briefly highlight two of these advances here.

First is the work of Spoon et al. (2013), who used *Herschel* PACS spectroscopy to study the properties of the hydroxyl (OH) feature at 119 μm in 24 low-redshift ULIRGs. The OH profiles were found to display a range in shapes; some were seen purely in absorption, some purely in emission, but at least two-thirds of the sample displayed prominent P-Cygni profiles, consistent with outflowing molecular gas. In some cases the maximum outflow velocities exceeded 1000 km s^{-1}. A crude negative correlation was observed between the equivalent width of the OH 119 feature, and the strength of the Silicate feature at 9.8 μm (Figure 1), consistent with the most powerful outflows occurring in moderately to deeply embedded ULIRGs, rather than lightly obscured systems. Furthermore, the maximum outflow OH 119 speed was found, in general, to correlate with AGN luminosity, but not with starburst luminosity (Figure 2). This is consistent with the AGN rather than star formation powering the outflow, presumably via radiation pressure on dust grains (e.g. Martin 2005). Finally, a small number of sources also showed asymmetries in their [C II] 158 μm profiles, consistent with disruption of the neutral gas reservoir by the outflow.

These results are consistent with *powerful* AGN driven molecular outflows being common among ULIRGs, particularly in deeply obscured systems. This suggests that quasar mode feedback is a key phase among ULIRGs, well before the AGN is visible as a classical QSO. This is consistent with expectations from models (Di Matteo et al. 2005), and implies that the large number of obscured AGN in high redshift systems (e.g. Martínez-Sansigre et al. 2005) could in some circumstances have a profound impact on their host galaxies, even though they are not bolometrically dominant.

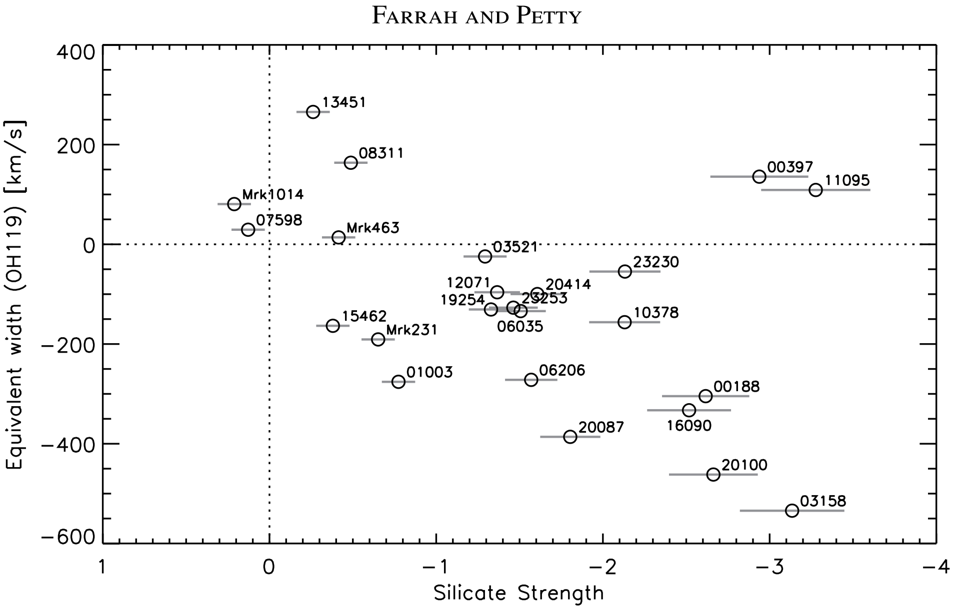

Figure 1. The equivalent width of the OH 119 feature as a function of silicate optical depth. A negative equivalent width means the OH 119 absorption component is stronger than the OH 119 emission component. A positive silicate strength means the 9.8 μm silicate feature is in emission.

Second is the work of Farrah et al. (2012), which studied the "FeLoBAL" class of QSOs. FeLoBAL QSOs (Hazard et al. 1987; Hall et al. 2002; Gibson et al. 2009) have recently emerged as excellent candidates for being closely linked to both powerful AGN-driven winds, and to a brief ($\sim 10^{7.5}$–10^{8} yr) transition stage in which a starburst is nearing its end, and a young QSO is emerging. The evidence for the former is twofold. First, FeLoBAL QSOs, like all BAL QSOs, exhibit broad, deep UV absorption troughs that are clear signatures of radiatively driven, AGN powered winds. Second, FeLoBAL QSOs are the only class of object for which the winds have been shown to extend several kiloparsecs into the host galaxies (Moe et al. 2009), implying that the winds can directly affect star formation. The evidence for the latter is that the FeLoBAL QSOs are always extremely IR-luminous (Farrah et al. 2007), and sometimes harbour intense starbursts (Farrah et al. 2010) that are factors of several more intense than those seen in classical QSOs (e.g. Floyd et al. 2013). This contrasts with LoBAL QSOs, for which less than half are IR-luminous, and do not show high levels of star formation (compare e.g. Farrah et al. (2012) with Lazarova et al. (2012)).

Farrah et al. (2012) investigated the relationship between wind strength and star formation rate in FeLoBAL QSOs using data from the *Spitzer* space telescope. Wind strengths were estimated from the Balnicity Index of the Mg II 2799Åline; the low ionization state and (relatively) long wavelength of this line mean it is a reasonable proxy for the kinetic flux in the BAL wind. Star formation rates and AGN luminosities were estimated by fitting radiative transfer models to the IR SED across 4–160 μm. It was found that the strength of the winds anti-correlates with the contribution from star formation to the total IR luminosity, with a much higher chance of seeing a high starburst contribution in systems with weak outflows than in systems with strong outflows (Figure 3 left). Several possible explanations were tested to explain this result. The most plausible explanation was found to be that the wind is acting to quench star formation in the host galaxy. An alternative explanation, that the effect could be explained simply by a generally more luminous AGN, with no relation to the starburst, was rejected at significant confidence (Figure 3 right). This paper thus demonstrates that quasar mode feedback is **in the act of happening** in FeLoBAL QSOs. Not only are they going through the $\sim 10^{7}$–10^{8} year phase between a ULIRG and a QSO, but are also going through a phase during which quasar driven winds are actively suppressing star formation.

3. FUTURE PROSPECTS

The work of Farrah et al. (2012) and Spoon et al. (2013) provides some refinement to our observational understanding of quasar mode feedback in galaxy mergers (though with the caveat that FeLoBAL QSOs have not been directly linked to galaxy mergers). These papers suggest that quasar mode feedback can be significant from approximately partway through the initial encounter, while obscuration levels are still very high and the AGN may be invisible in the optical, until at least the reddened QSO stage, when obscuration is still significant but the AGN can be seen in the optical. Adopting canonical time-scales for a merger (10^{8-9} years), a classical QSO ($\sim 10^{8}$ years) and a feedback phase (10^{7-8} years), then this is consistent with quasar mode feedback having a significant impact on the host galaxy ISM only until at most shortly after the reddened QSO phase has ended.

SPICA will provide fundamental advances in our understanding of the obscured phases of quasar mode feedback. A key diagnostic will be high resolution measurements of multiple hydroxyl profiles, since this can provide a quantitative estimate of the mass flux in the molecular gas (e.g. González-Alfonso et al. 2012). It is also plausible that outflow activity may be seen in denser gas tracers, such as HCN. Assembling a dataset for of several tens of ULIRGs, with molecular

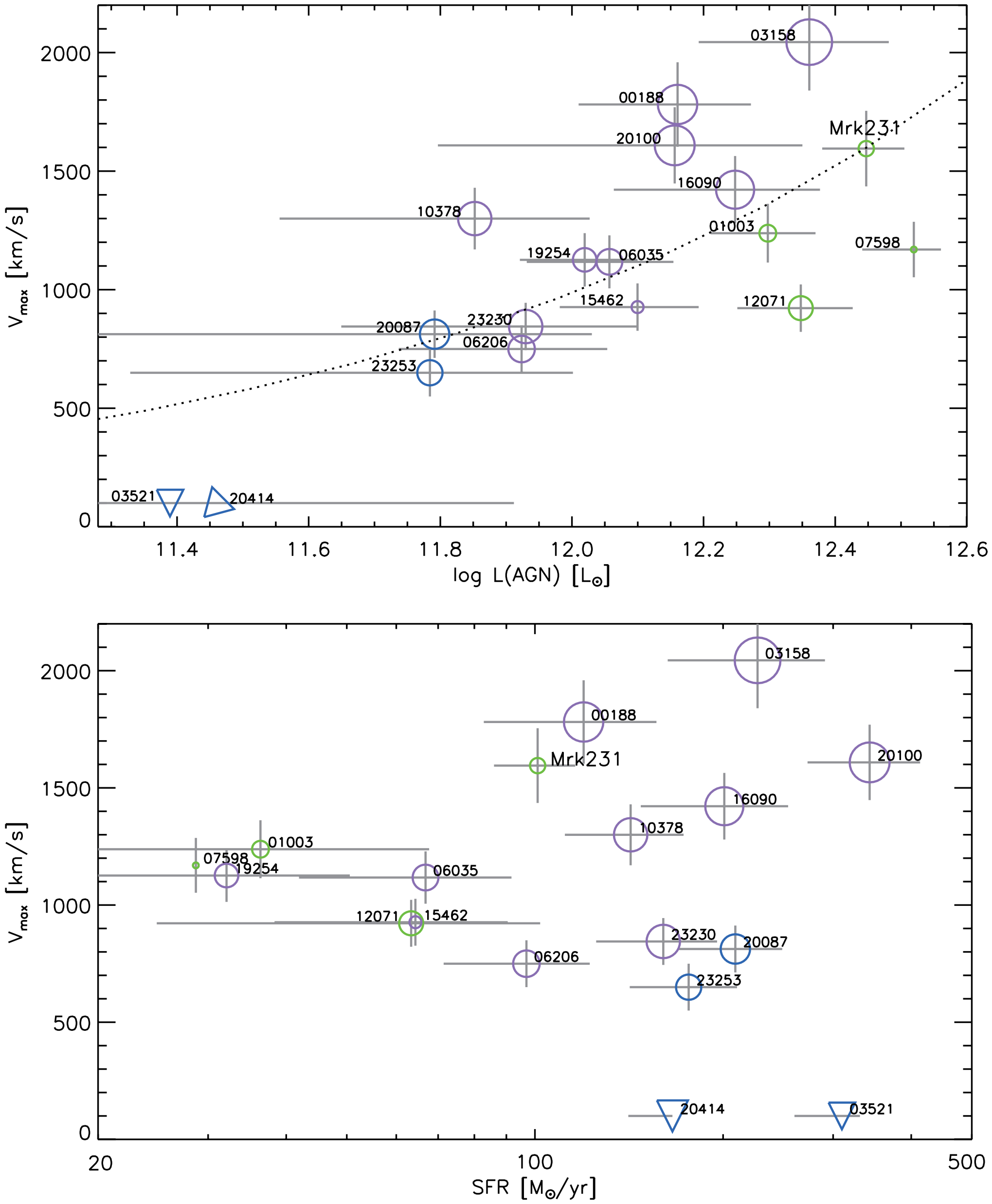

Figure 2. Upper panel: Maximum OH 119 outflow velocity as a function of AGN luminosity. The circle size is proportional to the silicate depth of the target. Triangles indicate upper limits. The dotted line is a power law fit to all but two sources: IRAS 03521 and 20414. The power law has the form $\log(v_{\rm max}/{\rm km\,s^{-1}}) = -2.64(\pm1.80) + 0.47(\pm0.15) \times \log(L_{\rm AGN}/{\rm L}_\odot)$. Lower panel: Maximum OH 119 outflow velocity as a function of star formation rate (SFR). In both panels starburst-dominated sources ($\alpha < 0.25$) are shown in blue, AGN-dominated sources ($\alpha > 0.75$) in green, and intermediate sources in purple.

outflow diagnostics across multiple density tracers for each ULIRG, would be a powerful tool in diagnosing the impact of the obscured AGN outflow phase as a function of both the ULIRG lifetime and the inherent diversity in the ULIRG population. For example, such a dataset could address the most prominent triggering mechanisms, possibilities include an AGN ‘threshold’ luminosity, and/or the appearance of a bar in the host morphology, which would provide an efficient way to channel gas and dust to the nuclear regions.

Comparison of these diagnostics to far-IR fine structure lines, e.g. the profile shape of [C II], would provide estimates of the effect of the outflow on the neutral gas reservoir, and on the relative effect of AGN driven outflows on the ISM, PDRs and H II regions. Comparison with mid-IR line profiles, particularly the [Ne V] 14.32 μm line, will give a a better understanding of how outflows relate to obscured AGN luminosity, and to outflow activity seen in the mid-IR line emitting gas. Perhaps most importantly; the relative brevity of the feedback phase means that *SPICA*s ability to assemble much larger samples than *Herschel* or *Spitzer* will be invaluable for picking apart degeneracies in the feedback process, and for assessing potentially differing levels of impact as a function of redshift.

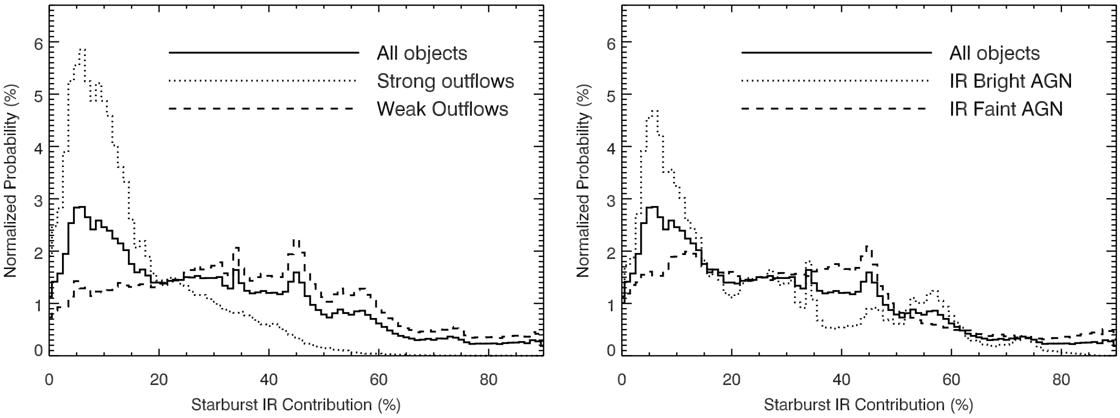

Figure 3. *Left:* Probability Distribution Function for starburst contribution divided according to their absorption strengths. The solid line is the PDF for the whole sample, the dashed line for objects with weak outflows (Balnicity Indices of $< 3500\,\mathrm{km\,s^{-1}}$), and the dotted line for objects with strong outflows (Balnicity Indices of $> 3500\,\mathrm{km\,s^{-1}}$). Error regions have been omitted for clarity, see Farrah et al. (2012) for the full versions. Objects with weak outflows show an significantly elevated chance of obtaining a starburst fractional luminosity in excess of 25 % compared to objects with strong outflows. *Right:* Probability Distribution Function for starburst contribution, this time divided according to their AGN luminosities; the dashed line is for objects with $L_{\mathrm{AGN}} < 10^{12.5}\,\mathrm{L}_{\odot}$ while the dotted line is for objects with $L_{AGN} > 10^{12.5}\,\mathrm{L}_{\odot}$. The difference between the two PDFs is significantly *smaller* than in the left hand figure, suggesting that the IR luminosity of the AGN is not driving the different starburst fractional luminosities seen in the samples divided by outflow strength.

Finally, there is the exciting potential of a mid-IR coronagraphic instrument. With resolution on kpc scales or finer, coupled with narrow-band filters that target both a star formation tracer and an AGN wind diagnostic (e.g. a PAH feature and the [Ne V] 14.32 μm line respectively), it may be possible to directly image the impact of an AGN-driven wind on star formation in the host galaxy, providing the most direct evidence possible that feedback is taking place.

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