Black Hole Winds at All Scales
Proceedings IAU Symposium No. 378, 2024
G. Bruni, M. Diaz Trigo, S. Laha & K. Fukumura, eds.
doi:10.1017/S1743921323003344

Atomic and Molecular Gas Outflows in FIR Bright QSOs at High-z

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Abstract. Feedback and outflows associated with a quasar phase are expected to be critical in quenching the most massive galaxies at high-z. Observations targeting the cool molecular and atomic phases, which dominate the mass and momentum budget of massive galaxy outflows and remove the direct fuel for star formation are, however, severely limited in high-z QSO hosts. We discuss two recent ALMA programs: one targeting molecular outflows in 3 $z \sim 6$ QSO hosts using the OH 119 μm absorption line and another targeting the diffuse, predominantly atomic gas in the halos surrounding 5 QSO host between $z \sim 2 - 4$ using the $OH^+(1_1 - 1_0)$ absorption line. Outflows are successfully detected in both samples and compared with outflows driven by high-z star-forming galaxies observed in the same lines. Both studies indicate that observing QSOs during the blow-out phase is crucial for studying the impact of the active nucleus on the ejection of gas from the host galaxy.

Keywords. galaxies: high-redshift — galaxies: starburst — quasars: general

1. Introduction

Feedback from star formation and black hole activity plays a key role in the evolution of galaxies and galaxy populations embedded in the cosmic web. Galaxy evolution is regulated by energy and momentum injected into the ISM via these processes which heat, disturb or eject gas that may have fueled future star formation. Outflows are an essential phenomenon required by models and simulations to reproduce observed disky-galaxy morphologies, metallicity gradients and the polluted circum-/inter galactic medium (Governato *et al.* 2010; Veilleux *et al.* 2005; Simcoe *et al.* 2004) as they preferentially remove low angular momentum and metal-enriched material from the centres of galaxies.

Regulated galaxy growth implies that the most rapidly evolving galaxies must also experience the most vigorous feedback. Luminous AGNs, or QSOs, are believed to play a major role in quenching star formation in the most massive galaxies, primarily dispersing the available molecular gas through a blow–out phase (Costa *et al.* 2018), halting star formation and exposing the previously obscured QSO nucleus. Energy from the central AGN can then escape uninhibited, injecting heat and turbulence directly into the circumgalactic medium (CGM) and preventing this material from falling back in and re-fueling the galaxy. Assuming this evolutionary track, Dusty Star-Forming Galaxies (DSFGs) harbouring QSOs are currently in their transition phase, however, the fraction of star-forming galaxies identified as optically luminous is small. This suggests a fast ($\sim$1Myr; Simpson *et al.* 2012) and therefore explosive transition phase resulting in significant gas outflows.

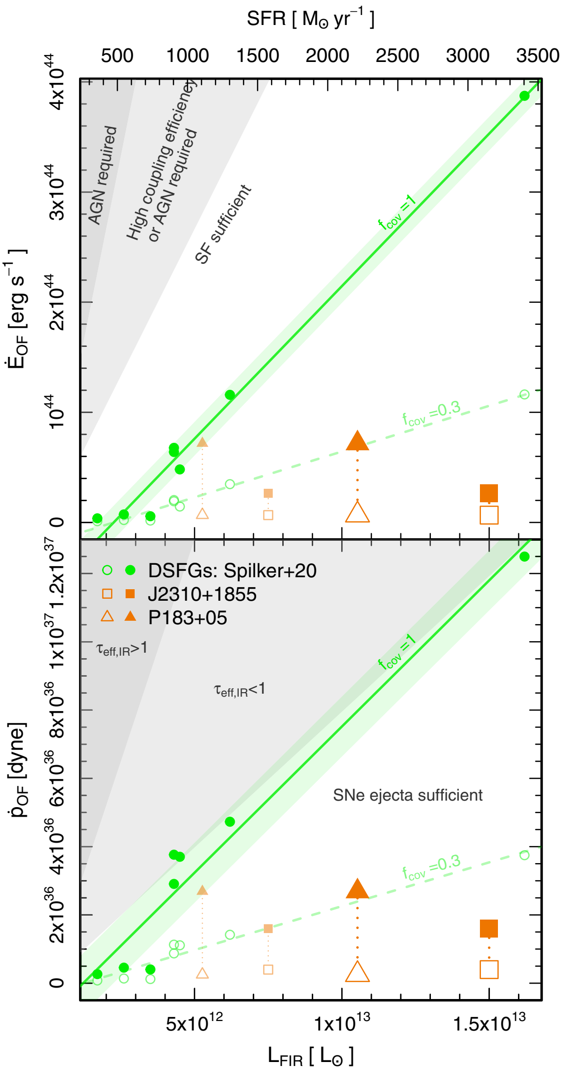

Figure 1. From Butler *et al.* (2023a): Comparing Molecular outflows from high-z unobscured QSOs with high-z DSFGs (Spilker *et al.* 2020b). The kinetic energy flux (top) and momentum flux (bottom) as a function of FIR luminosity and SFR. The unobscured QSOs (orange) do not require input from an AGN to drive their molecular outflows and in fact, appear to be suppressed after the blow-out phase compared to the DSFGs. This implies that the central AGN is not the dominant driving mechanism of outflows in the unobscured QSOs.

At high-z considerable work has begun on detecting and studying cool gas outflows in DSFGs using the $OH^+(1_1 - 1_0)$ (Shao *et al.* 2022; Riechers *et al.* 2021; Butler *et al.* 2021, 2023b) and OH 119 μm (Spilker *et al.* 2020b; Butler *et al.* 2023a) absorption lines, successfully showing that these lines are sensitive and reliable tracers. Observations in high-z QSOs, however, are greatly lacking. Here, we discuss two recent investigations of cool gas outflows in high-z QSO hosts using the $OH^+(1_1 - 1_0)$ and OH 119 μm absorption lines, aiming to fill this gap.

2. Overview

Butler *et al.* (2023a,c) presents OH 119 μm observations of three $z > 6$ unobscured dusty QSOs. They find blueshifted absorption, indicating molecular outflows, in two of

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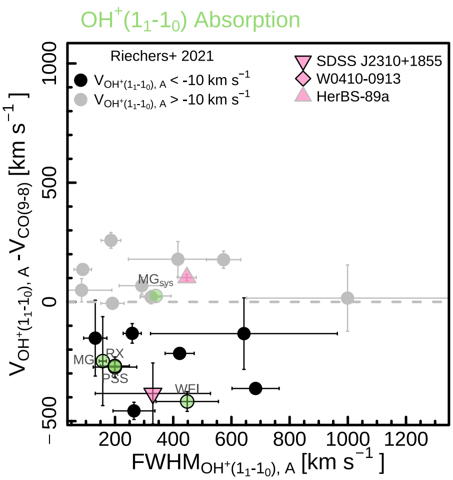

Figure 2. Adapted from Butler *et al.* (2023b): Comparing predominantly atomic gas outflows from high-z unobscured QSOs with high-z DSFGs (Riechers *et al.* 2021). The line width versus outflow velocity of the predominantly atomic gas: the outflows driven from the QSO sample (green) are not boosted with respect to the DSFG. This implies that the central AGN is not the dominant driving mechanism of outflows in the unobscured QSOs.

their sources. They compare the line and derived outflow properties of the two molecular outflows associated with the unobscured QSO hosts with molecular outflows observed in similarly FIR bright DSFGs at high-z (Spilker *et al.* 2020b).

In Fig. 1 the comparison between these samples in kinetic energy and momentum flux of the molecular outflows is shown. Here we see that the outflows driven from the unobscured QSO hosts are suppressed with respect to the DSFGs.

Butler *et al.* (2023b) targeted five high-z QSO hosts (four unobscured and one obscured) with the $OH^+(1_1 - 1_0)$ line. Outflows were detected in three QSO hosts with an additional tentative detection in a fourth and no detection of absorption in the fifth. The one obscured QSO host was the only source to display systemic OH^+ absorption (along with its blue-shifted absorption). Fig. 2 compares the full-width half maximum and Doppler shifted velocity of the OH^+ absorption components between the QSO and DSFG samples. They find no offset in either outflow velocity or outflow line width between the two samples, again providing no indication that the central AGN significantly contributes to or boosts the neutral atomic outflows in high-z QSOs.

3. Implications

Despite the dusty QSO hosts in these samples harbouring both an active nucleus and comparable star formation rates as their comparison DSFG samples, their neutral atomic and molecular outflows are not boosted. Both studies, however, note that they contain only unobscured QSOs (except one obscured QSO in Butler *et al.* 2023b), which have already gone through their 'blow-out' phase in which the obscuring material directly surrounding the central AGN is removed. During this phase, radiation from the AGN is trapped inside the QSO host and is believed to significantly contribute to the outflow of central gas via radiation pressure (Costa *et al.* 2018). Once removed, radiation is able to efficiently escape the host galaxy through the cleared path and thus may contribute significantly less to the ejection of cool gas.

Venemans *et al.* (2018, 2020) showed in their studies of high-z unobscured QSOs that no trend between the FIR luminosity, both spatially integrated and in just the central regions, and the UV magnitude of the central QSO is seen. Observation of high-J CO lines in several sources (Gallerani *et al.* 2014; Decarli *et al.* 2022) similarly provides a picture where the central QSO does not contribute significantly to the host galaxy. Thus, the conclusion of the studies discussed in this proceeding is that QSO hosts currently going through their blow-out phase should be the targets for studies aiming to investigate the true impact of the central active nucleus on the ejection of neutral and molecular gas from the host galaxy. In this way, we will be able to capture the point in a galaxy's evolution where the central active nucleus is most directly impactful on the host galaxy and therefore provide a better understanding of its role in the quenching of massive galaxies at high-z.

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