Quasar Feedback Survey – the impact of jets and multi-phase outflows on their host galaxies

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Active galactic nuclei (AGN) are the sites of growing supermassive black holes at the centre of galaxies [1]. Through accretion of matter, AGN can produce tremendous amounts of energy, that could also potentially exceed the binding energy of their host galaxies [2]. With this amount of energy available, if it can efficiently couple to the gas extending from the vicinity of the AGN to galactic scales, the AGN could cause significant impact (known as 'feedback') on their host galaxies by either facilitating or suppressing the star-formation (see review in [3]). This 'AGN feedback' has become an imperative ingredient in cosmological galaxy formation simulations for them to reproduce key observables of galaxy populations and intergalactic material [4]. However, understanding how this process occurs in the real Universe, particularly in the case of the most powerful AGN (i.e., quasars; $L_{\rm bol} \geq 10^{45}$ erg s^{-1}), remains a challenge.

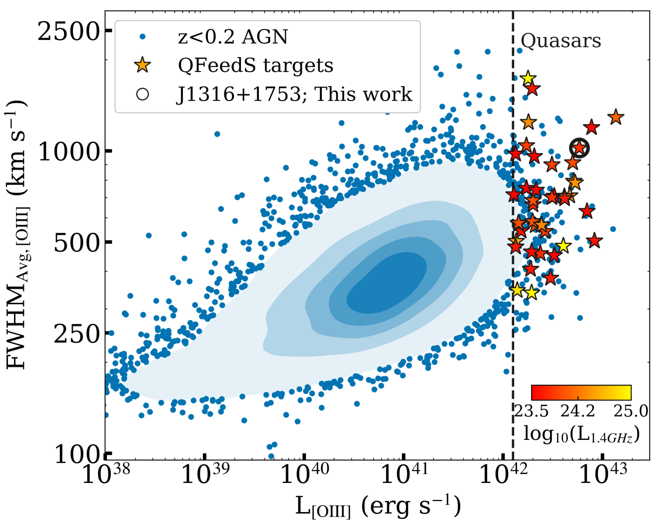

Figure 1: [O III] FWHM versus $L_{\rm [O\ III]}$ for $z < 0.2$, spectroscopically-selected AGN from [6], represented as blue data points and density contours. Stars represent the 42 QFeedS targets, color-coded for their radio luminosity.

Quasar Feedback Survey

Quasar Feedback Survey (QFeedS; Figure 1; [5]) aims to address the challenges outlined above by studying the spatially-resolved multi-wavelength properties of 42 relatively low redshift ($z < 0.2$) quasar host galaxies. Using this redshift range allows us to obtain sensitive, high spatial resolution observations, whilst also yielding a reasonable sample of powerful quasars ($L_{\rm bol} \geq 10^{45}$ erg s^{-1}) representative of $L_\star$ at the peak cosmic epoch of growth, where quasar feedback is expected to dominate ([1]). We study spatially-resolved radio observations using 6 GHz VLA data, which provides important insights into the prevalence and properties of radio jets in what is a representative and predominantly 'radio-quiet' quasar sample [7, 5]. Radio-loud quasars have come to be known for their strong feedback effects, however high resolution radio data has now come to reveal how radio-quiet quasars could also be housing radio-jets capable of causing turbulence in the host galaxy, as we also show in this work.

Low-Power radio jets driving Multi-phase gas perpendicular to host-galaxy

We present MUSE and ALMA data of J1316+1753, a luminous $z = 0.15$, type-2 quasar selected from the Quasar Feedback Survey. This target represents one of the most [O III] luminous sources from the survey ($L_{\rm [OIII]}$=$10^{42.8}$ erg s^{-1}) and exhibits a broad [O III] emission-line profile (FWHM$\sim$1300 km s^{-1}; Figure 1). Radio imaging of this source reveals low-power radio jets ($P_{\rm jet}$ $\sim$$10^{44}$ erg s^{-1}) that are compact, reaching only 1 kpc in projected distance from the core. Furthermore, the jets are inclined into the plane of the host galaxy disk.

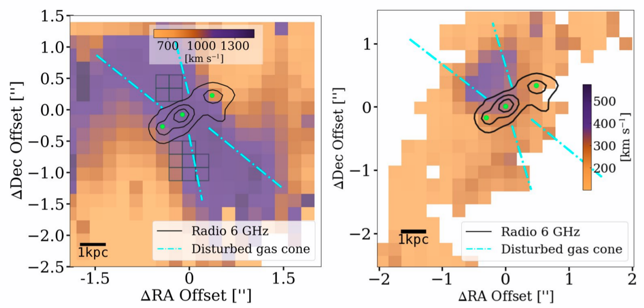

Figure 2: Kinematic analysis of the ionised (left) and molecular (right) gas in the central region around the jet, using maps of the non-parametric values of the [O III] and CO (3–2)emission-line fits. The black contours in each map represent the 6 GHz radio emission at levels of [32,16,4] RMS$_{\rm radio}$. The three cyan dots represent the radio core (HR:A) and jet hot spots (HR:B and HR:C). A 1 kpc scale bar is shown in each of the maps. The emission corresponding to an enhanced velocity-dispersion (W_{80} ≥1000 km s^{-1} *in left panel* and ≥400 km s^{-1} *in right panel*), suggests a bi-conical structure in the region perpendicular to the jets (indicated by the dash-dotted cyan lines).

Our data enables us to map the stellar kinematics (traced with stellar absorption features), warm ionised gas properties (traced with optical emission-lines) and the cold molecular gas properties (traced with the CO(3–2) emission-line). On galaxy scales, both the molecular gas and ionised gas broadly follow the stellar gravitational motions [8]. However, across the central few kiloparsecs, both gas phases reveal high velocity nongravitational motions and we observe evidence of jet-induced feedback.

Ionised gas with very high velocity-dispersion (i.e., $W_{80} = 1000-1300\,\mathrm{km\,s^{-1}}$) is seen to propagate outwards in a bi-cone from just behind the radio hot spots, travelling perpendicular to the galaxy disk and seen in projection as extending to at least 7.5 kpc from the nucleus (see Figure 2). The highest inferred electron densities of the ionised gas are found within these bi-cones (as inferred from the [S II] doublet). This turbulent gas is also seen in the molecular gas phase. However, it is 3 times less extended (and only in one direction) with 3 times lower velocity-dispersion (i.e., $W_{80} \sim 400\,\mathrm{km\,s^{-1}}$) compared to ionised gas phase (see Figure 2).

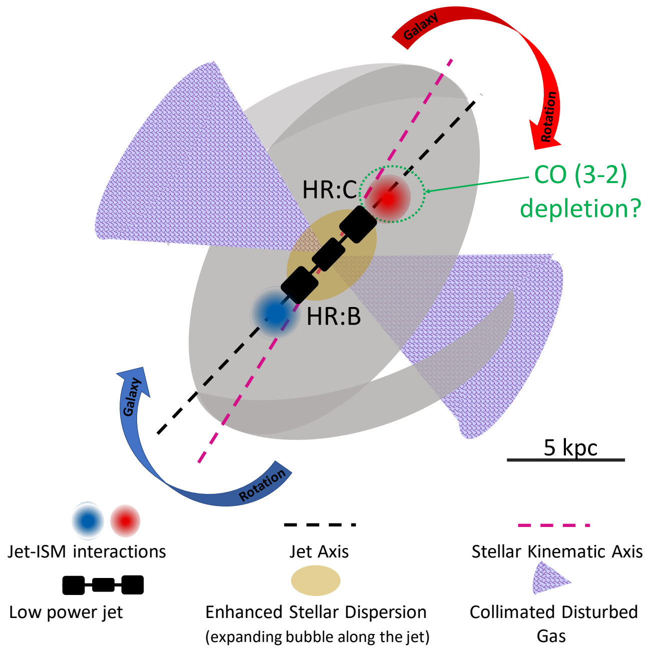

Figure 3: A schematic view of the galaxy J1316+1753 to highlight the key observations identified in this work. The line-of-sight view (where North is up and East is to the left); A legend shows the different symbols used to represent the main features of interest.

In Figure 3, we present a schematic of the galaxy from line of sight illustrating the observed features. We observe two bright and high velocity offset ionised gas components (separated by 441 $\mathrm{km\,s^{-1}}$) concentrated at the positions of the jet hot spots and that appear to propagate away from the jets, along the jet axis (see Figure 3). Furthermore, a $-100\,\mathrm{km\,s^{-1}}$ change in the molecular gas velocity is observed just beyond the brighter radio hot spot, with tentative evidence for depleted CO (3–2) emitting gas at the same location.

Strong spatial connection between the jets and stellar properties

We see a close alignment of the position angle of the stellar bulge with the radio-jet axis. Furthermore, the regions with the highest stellar velocity-dispersion (i.e., $\sigma_\star$ are seen to be lagging behind the jets, following the jet axis (see Figure 2 & 4 in [8]).

Implications for 'radio-quiet' AGN feedback

Our observations provide strong evidence for low power radio jets, inclined into the galaxy disk, having a direct impact on the multi-phase ISM inside the host galaxy of this type-2 quasar. Our observations are qualitatively consistent with the simultaneous positive and negative feedback effects observed in hydrodynamics simulations of jet-ISM interactions [9, 10, 11]. Specifically: (a) as the inclined, lower power jets move through the galaxy, it inflates a bubble of jet plasma which leads to a stronger interaction with the ISM; (b) as the jets propagate, they compress the gas in the disk also causing new stars to form in these regions, contributing to the formation of the stellar bulge and; (c) highly turbulent material is stripped and escapes above and below the galaxy disk, following the path of least resistance, resulting in removal of gas from the host galaxy.

Whilst jets have been seen to be dominant in lower power AGN, our observations reveal that jets can be the dominant feedback mechanism, even for this bolometrically luminous source, i.e., for an AGN currently in a 'quasar mode'. To understand the relative role and impact of jets and winds in quasars we are currently performing a similar multi-wavelength study of the wider population.

References

[1] Kormendy, J., Ho, L. C., 2013, ARA&A, 51, 511.
[2] Cattaneo, A., et al., 2009, Natur, 460, 213.
[3] Harrison, C. M., 2017, NatAs, 1, 0165.
[4] Vogelsberger, M., et al., 2014, MNRAS, 444, 1518.
[5] Jarvis, M. E., Harrison, C. M., Mainieri V., et al., 2021, MNRAS, 503, 1780.
[6] Mullaney, J. R., et al., 2013, MNRAS, 433, 622.
[7] Jarvis, M. E., Harrison C. M., et al., 2019, MNRAS, 485, 2710.
[8] Girdhar, A., Harrison, C. M., Mainieri V., et al., 2022, MNRAS, 512, 1608.
[9] Mukherjee, D., et al., 2018, MNRAS, 479, 5544.
[10] Mandal, A., et al., 2021, MNRAS, 508, 4738.
[11] Meenakshi, M., et al., 2022, arXiv, arXiv:2203.10251

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