Galaxy Evolution and Feedback across Different Environments
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Distant quasar host galaxies and their environments with multi-wavelength 3D spectroscopy

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Abstract. We have conducted a multi-wavelength survey of distant ($1.3 < z < 2.6$) luminous quasars host galaxies using the Keck integral field spectrograph (IFS) OSIRIS and laser guide star adaptive optics (LGS-AO) system, ALMA, HST and VLA. Studying distant quasar host galaxies is essential for understanding the role of active galactic nuclei (AGN) feedback on the interstellar medium (ISM), and its capability of regulating the growth of massive galaxies and their supermassive black holes (SMBH). The combination of LGS-AO and OSIRIS affords the necessary spatial resolution and contrast to disentangle the bright quasar emission from that of its faint host galaxy. We resolve the nebular emission lines Hβ, [OIII], [NII], Hα, and [SII] at a sub-kiloparsec resolution to study the distribution, kinematics, and dynamics of the warm-ionized ISM in each quasar host galaxy. The goal of the survey was to search for ionized outflows and relate their spatial extent and energetics to the star-forming properties of the host galaxy. Combining ALMA and OSIRIS, we directly test whether outflows detected with OSIRIS are affecting the molecular ISM. We find that several mechanisms are responsible for driving the outflows within our systems, including radiation pressure in low and high column density environments as well as adiabatic and isothermal shocks driven by the quasar. From line ratio diagnostics, we obtain resolved measurements of the photoionization mechanisms and the gas-phase metallicity. We find that the quasars are responsible for photoionizing the majority of the ISM with metalicities lower than that of gas photoionized by AGN in the low redshift systems. We are now obtaining detailed observations of the circumgalactic medium (CGM) of these systems with the Keck Cosmic Web Imager (KCWI). The gas in the CGM may play an essential role in the evolution of these galaxies.

Keywords. galaxies: active, evolution, high-redshift, jets, kinematics and dynamics, nuclei

1. Introduction

Feedback from active galactic nuclei (AGN) has become an integral part of galaxy evolution. Feedback from AGN is often used to explain the correlation between the mass of the SMBH and the mass and velocity dispersion of the host galaxy (Ferrarese & Merritt 2000; Gebhardt *et al.* 2000; McConnell & Ma 2013). Theoretically, transferring 0.1-5% of the AGN bolometric luminosity into an outflow can have a significant impact on the star formation properties of the host galaxy, which can help establish some of the observed local scaling relations (Hopkins & Elvis 2010; Zubovas & King 2012).

We have surveyed 11 radio-loud quasars in the distant Universe ($z \sim 2$) to study the impact of quasar driven outflows on their respective host galaxies during the peak epoch of galaxy and SMBH growth (Madau & Dickinson 2014; Delvecchio *et al.* 2014). The observations were undertaken with adaptive optics and an integral field spectrograph (IFS) at the W. M. Keck observatory. The primary goal of the survey was to search for

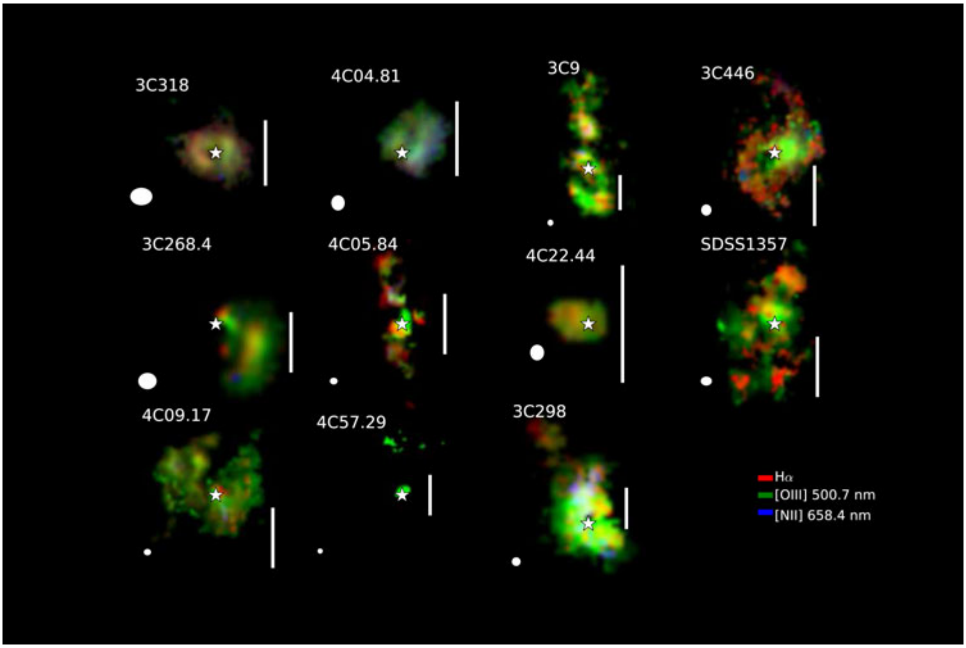

Figure 1. OSIRIS - LGS observations of 11 quasar host galaxies in our sample. Each image is a three-color composite where red is color-coded to Hα, green to [O III] and blue to [N II] . The location of the subtracted out quasar is represented by a white star, the ellipse in the lower-left corner shows the resolution of our observations (typically ∼0.1″), and the scale bar to the right of each source represents 1″(8.4 kpc).

ionized outflows using nebular emission lines redshifted into the near-infrared, measure the galaxy masses, and explore the photoionization mechanism of the gas in these quasar host galaxies. In these proceedings, we present a snippet of the results from our survey. We present the details in two papers: Vayner *et al.* (2020a,b).

2. Discussion and Results

As part of our survey, we targeted optically luminous type-1 quasars with bolometric luminosities $>10^{46}$erg s^{-1}, with massive ($>10^9$ $M_\odot$) SMBHs. Such AGN typically outshine the light from their host galaxies; hence a careful removal of the unresolved quasar emission was necessary. We have devised a point spread function (PSF) subtraction routine using channels that contain emission from the broad-line region of the quasar to establish an image comprising of only the quasar emission. This image is then normalized and subtracted from the rest of the data channels leaving behind only the extended emission from the quasar host galaxy. Details on the PSF subtraction routine can be found in the following two papers from our survey: Vayner *et al.* (2016, 2020a).

Extended ionized emission is detected in 11 objects (Figure 1), comprising of photoionization from the quasar, massive young stars, and shocks. The quasar is responsible for producing the majority of the observed emission. We have placed line ratios from individual spaxels (spectral-pixels) on the BPT diagram as well as integrated values over the distinct regions to understand the spatially resolved photoionization mechanism and resolved gas-phase conditions (Figure 2). We find that the majority of our points lie outside the star formation and mixing sequence observed in the local Universe. Using photoionization models from Kewley *et al.* (2013a,b), we believe the main reason for the

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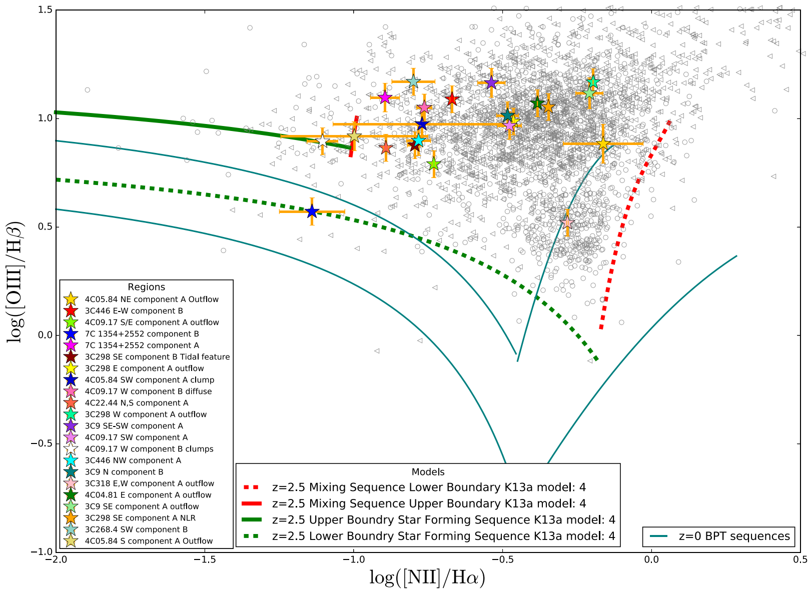

Figure 2. In this figure, we present line ratio diagnostics of individual resolved distinct regions. In grey, we plot the line ratios of individual spaxels, whereas the stars represent line ratios over integrated regions in each quasar host galaxy. The red and green curves show the best fit evolutionary models of the mixing and star-forming sequence from Kewley *et al.* (2013a), where on average, the gas photoionized by the quasar has a lower metallicity compared to that of galaxies with AGN in the local Universe. The boundary of the observed line ratios in the local Universe is shown with the teal curve.

offset is due to, on average lower metallicity in the gas photoionized by the quasar within our sample compared to that of local AGN.

We detect outflows in 10/11 sources on scales ranging from <1 kpc to 10 kpc. The outflow rates vary from 8-2400 $M_\odot$ yr^{-1}, with momentum flux ranging from 0.03-80 L_{AGN}/c, and energy rates of 0.01-1% L_{AGN}. In 5/11 sources, the momentum flux is above 2× L_{AGN}/c indicating that an adiabatic shock likely drives the outflows. The coupling efficiency in these objects is high enough for the outflows to have a significant impact on the star-forming properties of the host galaxy. In the rest of the objects, the outflows are likely driven by either radiation pressure on dust grains or an isothermal shock, and typically the coupling efficiencies in these sources are below the minimum value prescribed by theoretical work (Zubovas & King 2012). For the majority of the sources, the outflow rates at present are higher than those of star formation, and the paths of the outflow are inconsistent with regions of active star formation. The observed momentum flux ratios and coupling efficiencies between the kinetic luminosity of the outflow and bolometric luminosity of the quasar are within the range observed in other studies of ionized outflows in the distant universe (Figure 3).

For nine objects, we can measure both the galaxy velocity dispersion and the dynamical mass of the host galaxy. Combining with the mass of the SMBH, we can compare these systems to the local scaling relations between the mass of the SMBH and the velocity dispersion and mass of the galaxy. Our systems are both offset from the $M_\bullet - \sigma$ and $M_\bullet - M_*$ relationships. This offset indicates a substantial growth in stellar mass is necessary from z ∼ 2 to present-day if these systems are to evolve into the present-day elliptical galaxies. Combining with our previous results, we find that the galaxies experience feedback before assembling on the local scaling relations and before the ISM is enriched to a level observed in massive local galaxies.

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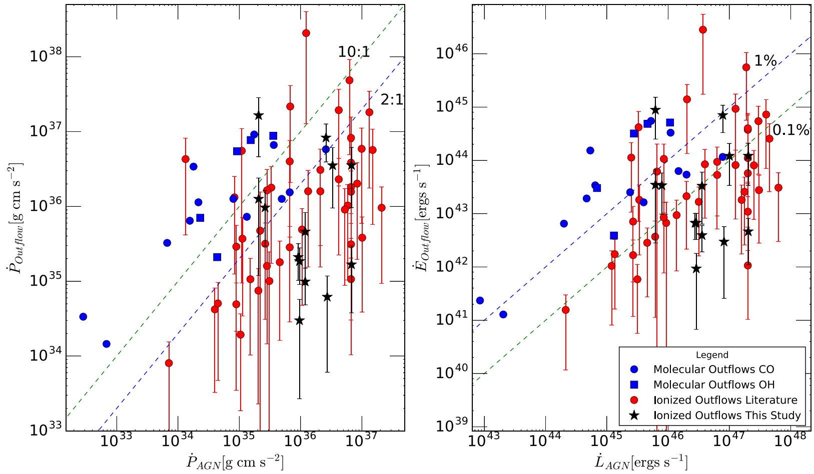

Figure 3. On the left, we plot the momentum flux of our outflows with a black star against the momentum flux of the quasar accretion disk. We plot a line of constant ratio at 2:1 between the momentum flux of the outflow and the accretion disk. Points above the 2:1 line represent outflows driven by an adiabatic shock, while points below the 2:1 are likely driven by an isothermal shock or radiation pressure on kpc scale. Red circles represent ionized outflows at z ∼ 2 computed in the same manner as our own. Blue points represent molecular outflows mainly at low redshift. On the right, we plot the kinetic luminosity of the outflow against the bolometric luminosity of the outflow. The green dashed curve represents the minimum coupling efficiency (0.1%) prescribed by theoretical work necessary for AGN driven outflows to affect the star-forming properties of their host galaxies.

We are currently undertaking an observing campaign to map the circum-galactic medium (CGM) of these systems to understand their subsequent evolution from z ∼ 2 to the present day. Likely, these systems host a massive gas reservoir in the CGM that can accrete material to fuel future star formation that will increase the stellar mass of the galaxies and enrich their ISM.

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