Uncovering Early Galaxy Evolution in the ALMA and JWST Era
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Massive quasar host galaxies in the reionisation epoch

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Abstract. Luminous quasars are powered by accretion onto supermassive black holes. Such luminous quasars have been discovered up to the highest redshifts, $z > 7$. Here we discuss recent observations of the host galaxies of luminous quasars at $z \gtrsim 6$. We do not find a correlation between ongoing black hole growth and star-formation rate in the high redshift quasars, possibly indicating that black holes and their hosts do not co-evolve. We further show that even with high spatial resolution observations of the gas kinematics, dynamical mass estimates remain highly uncertain and should be used with caution.

Keywords. cosmology: observations, galaxies: high-redshift, galaxies: ISM, galaxies: active

1. Introduction

In the local universe, a fundamental observational result in extragalactic astronomy is the tight correlation between the mass of the central black hole and the mass of the bulge of its host galaxy (Kormendy & Ho 2013). At first glance, such a correlation suggests that bulges and black holes co-evolve, increasing their mass simultaneously. However, recent work has questioned this co-evolution, especially at low redshift, and suggests this correlation is the end result of concomitant growth of bulges and supermassive black holes at high redshift (Kormendy & Ho 2013). It is therefore important to study this correlation at the highest redshifts, $z > 6$, to explore if the tight correlation between the mass of the black hole and the mass of the bulge already has been established in the early universe. Unfortunately, the mass of high redshift quasar hosts can not be measured directly as the stellar light is outshone by the bright, central quasar. However, the host galaxy can be detected by the redshifted emission of gas and cold dust.

In the last decade, we have been targeting $z \gtrsim 6$ quasars with mm facilities such as the PdBI/NOEMA interferometer and ALMA to characterise the host galaxies. Recently, we used ALMA to survey the [C II] line and the underlying dust continuum emission in 27 quasar host galaxies at $z > 5.94$. Even with less than 10 minutes on-source integration time, a very large fraction of the targeted quasars was detected: >85% of the quasar hosts showed significant [C II] emission (with [C II] luminosities between 10^9 and $10^{10}\,L_\odot$; Decarli *et al.* 2018) and all were detected in the dust continuum (with continuum flux densities between 0.1 and 6.0 mJy; Venemans *et al.* 2018). This high detection rate allowed us for the first time to study quasar host galaxies at the end of the reionisation epoch as a population. In this proceedings we will focus on the star-formation rates and masses of the quasar host galaxies, and compare them with the mass and growth of the black hole.

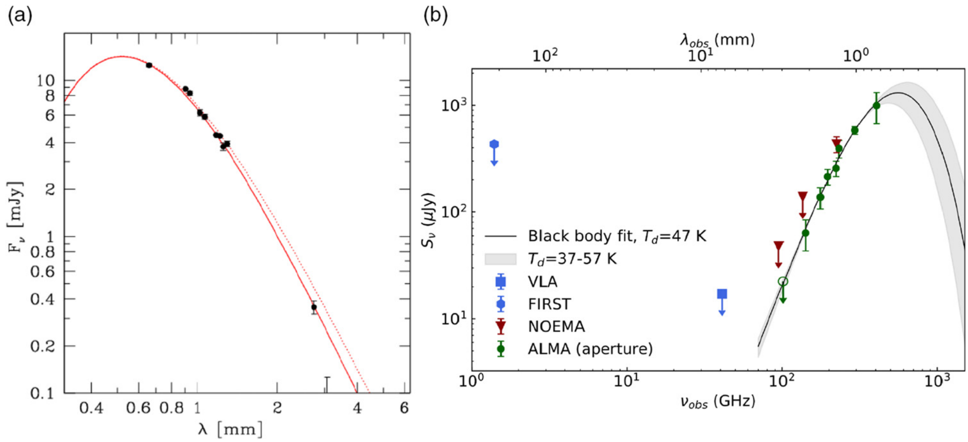

Figure 1. Dust spectral energy distribution of two quasar host galaxies at $z > 6$. **(a)** Dust SED of P183+05 at $z = 6.44$ (Decarli *et al.* 2018). The continuum has been detected at 4 different wavelengths ranging from 88 μm to 370 μm in the rest-frame. A modified black body fit gives a temperature of $T_d = 45 \pm 1$ K (Decarli *et al.* in prep). **(b)** Dust SED of J1342+0942 at $z = 7.54$ (Bañados *et al.* 2018; Venemans *et al.* 2017b). A modified black body with $T_d = 47$ K fits the data well (Novak *et al.* 2019).

2. Dust spectral energy distribution

First of all, to estimate the total infrared luminosity and to obtain a constraint on the star-formation rate in the host galaxy, we need to know the shape of the dust spectral energy distribution (SED). The dust SED is often described as a modified black body with a dust temperature T_d and emissivity index β. Based on submm and mm observations of very luminous and lensed quasars at $2 < z < 6$, Priddey & McMahon (2001) estimated $T_d = 41$ K and $\beta = 1.95$ while Beelen *et al.* 2006 measured an average $T_d = 47$ K and $\beta = 1.6$. These values have been subsequently used in the literature to derive FIR luminosities of $z > 6$ quasar host galaxies from single continuum band measurements (e.g. Wang *et al.* 2013; Willott *et al.* 2015; Venemans *et al.* 2016; Izumi *et al.* 2018). Recently, we tested this assumption by measuring the dust continuum of several $z > 6$ quasar host galaxies at multiple frequencies, which allowed us to constrain the shape of the dust SED and to verify whether the canonical values of $T_d = 47$ K and $\beta = 1.6$ are valid very high redshift quasar hosts. Two dust SEDs of $z > 6$ quasar hosts are shown in Figure 1. Both dust SEDs are consistent with the canonical value $T_d = 47$ K, assuming a fixed slope of $\beta = 1.6$. The best fit temperature of the dust in the luminous quasar P183+05 at $z = 6.44$ is $T_d = 45 \pm 1$ K (Figure 1a; Decarli et al. in prep), while for the fainter quasar host J1342+0942 at $z = 7.54$, a dust temperature $T_d = 47$ K fits the dust SED well (Figure 1b; Novak *et al.* 2019). These results justify the use of a single modified black body with $T_d = 47$ K and $\beta = 1.6$ to derive the FIR luminosity of quasar host galaxies at $z > 6$.

We can now investigate how the black hole and galaxy relate to each other by comparing the luminosity of the quasar $L_{\rm bol}$ derived from the absolute UV luminosity (a proxy for black hole growth), and the FIR luminosity (a proxy for star formation). In Figure 2 we plot the FIR luminosity derived from observed 1 mm continuum detections of $z > 5.7$ quasar host galaxy (assuming that the dust SED can be described by a modified black body with $T_d = 47$ K and $\beta = 1.6$, see discussion above) as a function of quasar brightness. We do not find a correlation between the brightness of the central source and that of the dust: for a given quasar brightness, the FIR luminosity of the host galaxy can differ more than an order of magnitude. First of all, this argues against a strong contribution of the

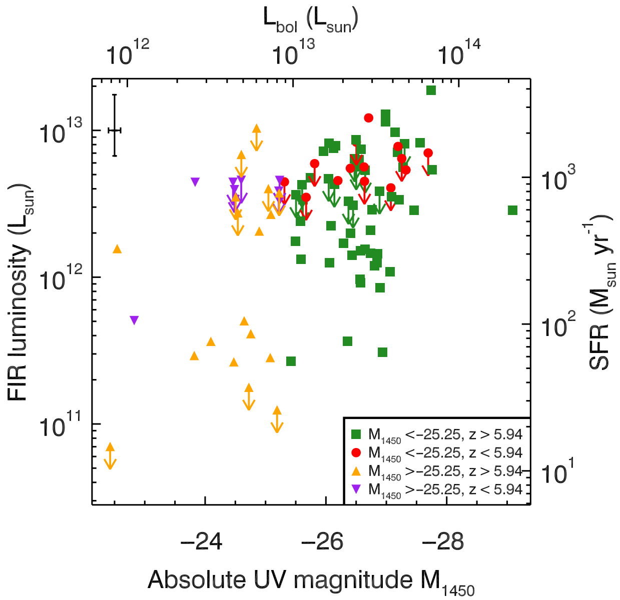

Figure 2. FIR luminosity of $z > 5.7$ quasars as a function of the absolute UV magnitude $M_{\rm UV}$. The green symbols are objects in a region of the parameter space that is highly complete. No correlation is apparent between the brightness of the quasar and the strength of the dust emission (adapted from Venemans *et al.* 2018).

quasar to the heating of the dust. The apparent lack of correlation between black hole growth and the stellar mass growth (as traced by the dust emission) indicates that at these high redshifts, the black hole and its host galaxy do not grow simultaneously. A possible explanation of our results is that the time scales of black hole accretion and star formation are vastly different. Furthermore, strong feedback from the central quasar could suppress the star formation in the host galaxy by removing the dusty interstellar medium (e.g. Hickox *et al.* 2014; Lapi *et al.* 2014; see Venemans *et al.* 2018 for a detailed discussion).

3. The mass of quasar host galaxies

While we do not find a clear correlation between the growth of the black hole and the star-formation rate, locally the correlation has been found between the **mass** of the black hole and that of the host galaxy. With current instrumentation, we cannot measure the stellar mass in the quasar host directly as the central quasar vastly outshines the light of the stars (e.g. Decarli *et al.* 2012). This will change in the near future, as observations with the *James Webb Space Telescope* will open up the potential to finally detect the stars in $z > 6$ quasar host galaxies. As an alternative, dynamical masses of the host galaxies (used as proxy for the stellar mass) have been computed in the literature from the extent and kinematics of the [C II] emission line (e.g. Wang *et al.* 2013; Willott *et al.* 2015; Venemans *et al.* 2016; Izumi *et al.* 2018). Based on these dynamical mass estimates, several groups concluded that the host galaxies of luminous quasars with black holes of $> 10^9\,M_\odot$ are less massive than expected based on the local relation (or the black holes are too massive, see e.g. Decarli *et al.* 2018). In contrast, other groups mostly targeting fainter quasars (powered by black holes $\ll 10^9\,M_\odot$) found that such $z \sim 6$ quasars are already located on the local relation (e.g. Izumi *et al.* 2018).

This lack of consensus between different groups might be a result of the large uncertainty in the dynamical mass measurements. Typically, dynamical mass estimates are

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derived from unresolved [C II] measurements under the assumption that the gas is located in a thin, rotating disk. In this case, the dynamical mass $M_{\rm dyn}$ can be computed using:

$$M_{\rm dyn} = R_{\rm [CII]}\,(0.75\,{\rm FWHM}/\sin i)^2\,/\,G, \tag{3.1}$$

with $R_{\rm [CII]}$ the radius of the [C II] emitting region and FWHM the full width at half maximum of the line (e.g. Walter *et al.* 2003; Wang *et al.* 2013; Willott *et al.* 2015; Venemans *et al.* 2016). Alternatively, if the gas is dispersion-dominated, the dynamical mass would be:

$$M_{\rm dyn} = 3/2\,R_{\rm [CII]}\,\sigma^2\,/\,G, \tag{3.2}$$

with σ the with of the [C II] line (e.g. Venemans *et al.* 2017a; Decarli *et al.* (2018)). The range in dynamical mass estimates from these two methods varies by a factor of 3, and the uncertainty on the inclination i often contributes another factor of a few uncertainty. High spatial resolution observations of the [C II] emission are required to reduce the large uncertainties in the dynamical mass estimates.

To resolve the structure of a distant host galaxy, explore its detailed kinematics and constrain the dynamical mass we obtained high spatial resolution (0.076″) ALMA observations of the host galaxy of quasar J0305–3150 at $z = 6.6$ (Venemans *et al.* 2019). The results are shown in Figure 3. Both the continuum and the [C II] emission are spatially resolved, and the emission is extended over ∼5 kpc. The gas distribution and kinematics, as traced by the [C II] emission, are highly complex. There is a pronounced lack of [C II] emission toward the east of the quasar. This cavity in the [C II] emission is also seen in the dust continuum observations. In general, the continuum and [C II] emission trace similar structures, the main difference being the bright peak in the continuum.

From the mean velocity map of the [C II] emission (third panel in Figure 3) it is evident that the position of the accreting black hole coincides with the kinematic center of the [C II] emission. It is also located at the center of the global [C II] emission. Generally, the gas exhibits some ordered motion along the line of sight, with the gas having positive line–of–sight velocities toward the east and negative velocities toward the west. The gas with the highest velocities — that was already seen at positive velocities toward the northeast in the low-resolution data (Venemans *et al.* 2016) — is now clearly separated, both spatially and in frequency. It is therefore likely that this is a companion galaxy close to the quasar host. Furthermore, the new data with the improved sensitivity reveal the presence of two additional [C II] emitters within 40 kpc at the same redshift as the quasar (Venemans *et al.* 2019).

The unique distribution and kinematics of the [C II] emission (Figure 3) cannot be explained by a simple model. Plausible scenarios are that the gas is located in a truncated or warped disk, or the holes are created by interactions with nearby galaxies or due to energy injection into the gas (Venemans *et al.* 2019). In the latter case, the energy required to form the cavities must originate from the central active galactic nucleus, as the required energy far exceeds the energy output expected from supernovae. This energy input into the gas, however, does not inhibit the high rate of star formation of $1500\,M_\odot\,{\rm yr}^{-1}$ (Venemans *et al.* 2016). Both star formation and black hole activity could have been triggered by interactions with satellite galaxies that are discovered in our ALMA data via their [C II] emission.

To summarize, our high spatial resolution imaging of a quasar host galaxy at $z = 6.6$ shows that its formation is a complex and chaotic process. We find that the interstellar medium (ISM) in the quasar host has not yet settled in a simple disk. Based on this study, we conclude that deriving dynamical masses of quasar host galaxies from low-spatial resolution observations is highly uncertain and generally cannot be used to compare the mass of the black hole with that of its host galaxy.

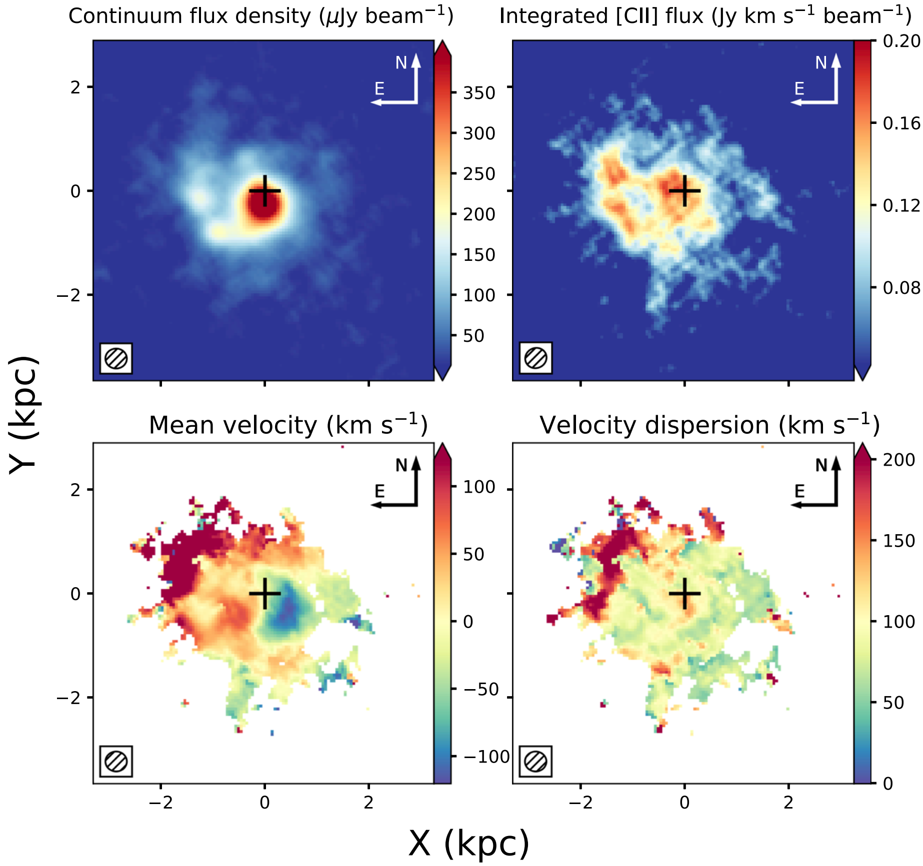

Figure 3. Dust and [C II] intensity maps (top rows) and [C II] velocity and dispersion maps (bottom row) of the host galaxy of the quasar J0305–3150 at $z = 6.6$. The cross indicates the location of the quasar. Both the gas distribution and the kinematics point to a complex system. Adapted from Venemans *et al.* (2019).

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