DOI: 10.18727/0722-6691/5039

ALMA Observations of $z \sim 7$ Quasar Hosts: Massive Galaxies in Formation

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Luminous high-redshift quasars are thought to be hosted by the most massive and luminous galaxies in the early Universe. Over the past few years, we have discovered several quasars at $z \sim 7$ powered by > 10^9 $M_\odot$ black holes, which allow us to study the formation and evolution of massive galaxies at the highest redshifts. ALMA and PdBI/NOEMA observations have revealed that these $z \sim 7$ quasars are hosted by far-infrared-bright galaxies with far-infrared luminosities > 10^{12} $L_\odot$, indicating star formation rates between 100 and 1600 $M_\odot$ year^{-1}. High-resolution ALMA imaging of a quasar host at $z = 7.1$ shows that a high fraction of both the dust continuum and [C II] 158 µm emission comes from a compact region < 2 square kiloparsecs across. Observations of emission from CO and neutral carbon in our $z \sim 7$ hosts provide the first constraints on the properties of the interstellar medium and suggest that the gas heating is dominated by star formation.

Distant quasars: beacons in the early Universe

Among the outstanding important questions in astronomy are when the first galaxies formed, and what their physical properties were. Galaxy candidates have now been identified through deep optical/near-infrared imaging surveys out to redshifts of $z > 10$, only ~ 450 million years after the Big Bang (see, for example, the recent review by Stark, 2016). However, their faintness typically prohibits detailed studies of their nature and characteristics, and, often even their spectroscopic confirmation. Indeed, studying the detailed physical properties of these objects and their contribution to cosmic reionisation is one of the main drivers for the James Webb Space Telescope (JWST) and the next generation of large optical telescopes (in particular the ESO Extremely Large Telescope, ELT).

An effective way to learn more about the constituents of galaxies at the highest redshifts is to study the brightest (and most massive) members of this population. Such luminous galaxies are very rare and not found in the deep, pencil-beam studies that are typically used for high-redshift galaxy searches with, for example, the Hubble Space Telescope (HST).

Quasars are among the most luminous non-transient sources in the Universe. As a result they can be seen out to very high redshift, $z > 7$. Quasars are powered by (supermassive) black holes that accrete matter from their environment. The host galaxies of accreting supermassive black holes at $z > 2$ are among the brightest and most massive galaxies found at these redshifts (for example, Seymour et al., 2007). Therefore, an effective method to pinpoint the most massive and luminous galaxies in the early Universe is to locate bright quasars at the highest redshifts.

A crucial initial step is to find such bright quasars at large cosmological distances. This is extremely difficult as they are very rare (only one luminous quasar is expected at $z \sim 6$ per > 100 square degrees on the sky) and requires large optical/near-infrared surveys that cover a large area. Indeed, the Sloan Digital Sky Survey discovered about 20 bright quasars around $z \sim 6$ (less than 1 Gyr after the Big Bang), which are shown to host supermassive black holes (> 10^9 $M_\odot$; for example, Jiang et al., 2007; De Rosa et al., 2011). Direct imaging of the stellar light of the galaxies hosting these high redshift quasars via rest-frame ultraviolet/optical studies has proven very difficult, if not impossible. On the other hand, observations of the molecular gas in the host galaxies in the radio and (sub)-millimetre (targeting the rest-frame far-infrared emission) allow the determination of the total gas mass and dynamical mass of the hosts. In the last decade, it has been demonstrated that large reservoirs of metal-enriched atomic and molecular gas and dust can exist in massive quasar host galaxies up to $z \sim 6.4$ (see Carilli & Walter, 2013 for a review). These observations already provide tight constraints on models of galaxy formation and evolution (for example, Kuo & Hirashita, 2012; Valiante et al., 2014).

To further constrain the build up of massive galaxies, it is important to locate and study bright quasars at even higher redshifts. Over the last ten years, with the advent of wide-field near-infrared cameras, large near-infrared surveys started to image the sky to sufficient depth to uncover distant quasars. Using various public surveys, such as the UKIRT Infrared Deep Sky Survey (UKIDSS), the Visible and Infrared Survey Telescope for Astronomy (VISTA) Kilo-degree INfrared Galaxy survey (VIKING), the VISTA Hemisphere Survey (VHS), and the Panoramic Survey Telescope And Rapid Response System survey (Pan-STARRS1), we have discovered more than a dozen luminous quasars with redshifts above $z = 6.5$ (for example, Mortlock et al., 2011; Venemans et al., 2013, 2015).

When compared to the quasars found around $z \sim 6$, the absolute magnitudes, black hole masses (of ≥ 10^9 $M_\odot$) and (metal) emission line strengths of these new $z \sim 7$ quasars are remarkably similar (for example, De Rosa et al., 2014), indicating little evolution in the quasar properties over the 200 Myr between $z = 6$ and $z = 7.1$ (~ 25 % of the Universe's age at that time). Furthermore, not only are these $z > 6.5$ quasars among the most distant sources found today, but they also have luminosities that are about two orders of magnitude larger than those of galaxies found at similar redshifts. These $z > 6.5$ quasars therefore provide a good opportunity to gain crucial insight into the formation and evolution of massive galaxies at the highest redshifts, and to understand the origin of the apparent correlation between bulge mass and black hole mass found in nearby galaxies (for example, Kormendy & Ho, 2013). With the completion of the Atacama Large Millimeter/submillimeter Array (ALMA) we now have a state-of-the-art facility to study the host galaxies of distant quasars in detail.

The host galaxies of $z \sim 7$ quasars

To extend the study of quasar host galaxies to $z \sim 7$, we initiated a programme targeting all quasars discovered at $z > 6.5$ at mm wavelengths, independent of their far-infrared brightness, with the aim of sampling the range of properties of quasar host galaxies and investigating the

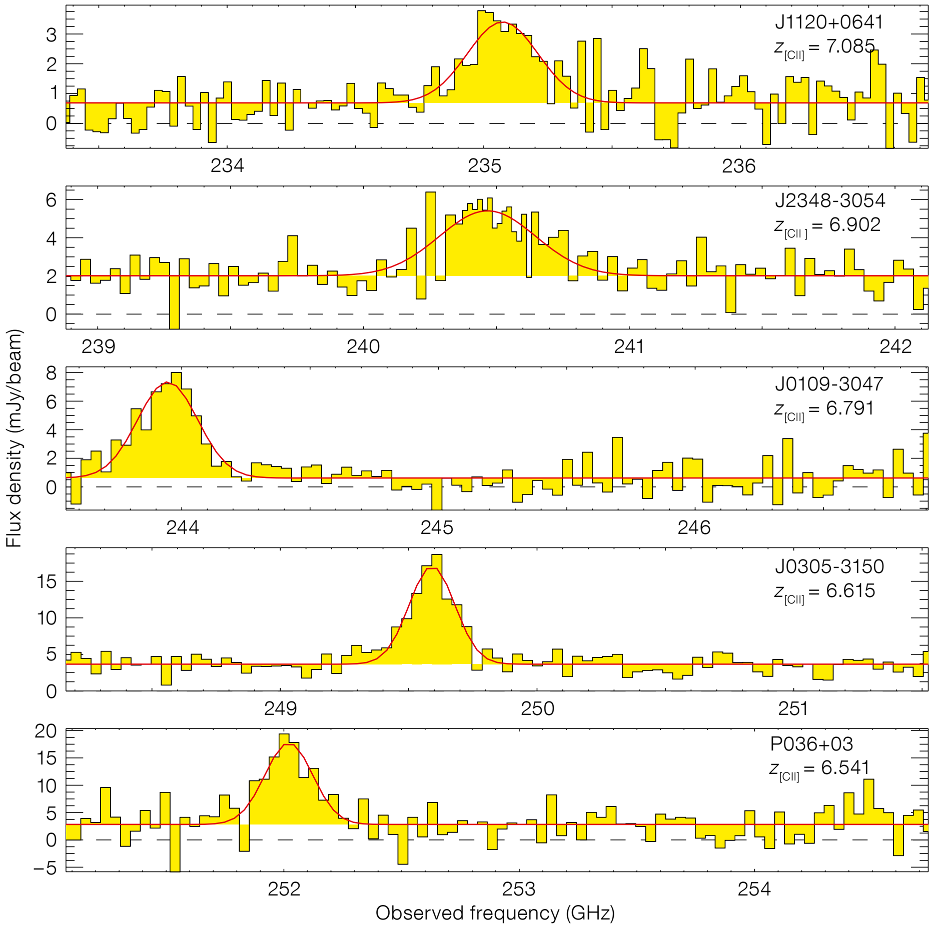

Figure 1. Compilation of [C II] 158 µm observations of five quasars at $z > 6.5$. The top four spectra are from our ALMA Cycle 1 programme (Venemans et al., 2016, 2017a) and the bottom spectrum is from PdBI (Bañados et al., 2015).

relationship between star formation and supermassive black hole growth at $z \sim 7$. Early studies of the host galaxies of $z \sim 6$ quasars, by their nature, concentrated on the far-infrared-bright quasars, and the results from these studies may have introduced a biased view of the characteristics of the typical galaxy hosting a luminous quasar in the early Universe. Using ALMA and the Institut de Radioastronomie Millimétrique (IRAM) Plateau de Bure Interferometer (PdBI), we imaged five $z > 6.5$ quasars, targeting the [C II] emission line (rest-frame wavelength of 158 µm) and the underlying dust continuum in the hosts (Figure 1). An additional seven quasars at $z > 6.5$ have been observed with ALMA and PdBI more recently and in each case the quasar host was detected (for example, Decarli et al., 2017). The host galaxies of $z > 6.5$ quasars show a range of properties, both in the strength and the extent of the far-infrared emission.

The first object in our project was the quasar J1120+0641, at $z = 7.1$ the highest redshift quasar known at that time (Venemans et al., 2012; Figure 1). The host galaxy of this quasar was found to display somewhat different characteristics in its far-infrared (FIR) properties; the far-infrared luminosity of $L_{\mathrm{FIR}} = (6\text{–}18) \times 10^{11}\,L_{\odot}$ is relatively faint compared to well-studied $z \sim 6$ quasar hosts (which have $L_{\mathrm{FIR}} \geq 5 \times 10^{12}\,L_{\odot}$; for example, Wang et al., 2013), and suggests a star formation rate of “only” 100–350 $M_{\odot}\,\mathrm{yr}^{-1}$.

Subsequent imaging of four additional $z > 6.5$ quasars revealed a host galaxy population with diverse properties (Figure 1). Both the [C II] emission and the dust continuum vary by a factor up to six among the quasar hosts. The [C II] line fluxes are in the range 1–5 Jy km s^{-1} (corresponding to between $1\text{–}6 \times 10^{9}\,L_{\odot}$) and the continuum flux densities range from 0.6 mJy to 3.3 mJy. Despite these variations, all the quasar hosts have far-infrared luminosities of $L_{\mathrm{FIR}} \geq 10^{12}\,L_{\odot}$ and can be classified as ultraluminous infrared galaxies (ULIRGs), in contrast to the vast majority of normal galaxies known at these redshifts. The high infrared luminosities indicate that stars formed in these quasar hosts at rates of at least ~ 100 $M_{\odot}\,\mathrm{yr}^{-1}$ and up to ~ 1600 $M_{\odot}\,\mathrm{yr}^{-1}$ (Venemans et al., 2016). Alternatively, using the [C II] luminosity to estimate the star formation rates in the quasar hosts results in very similar values. The far-infrared detections further imply that significant amounts of dust, $M_{\mathrm{Dust}} \geq 10^{8}\,M_{\odot}$, have already formed at $z \sim 7$, only 750 Myr after the Big Bang. Such high dust mass requires a very efficient dust production and/or a high stellar mass in the host galaxy (see, for example, Gall et al., 2011).

From the detection of the [C II] emission line, we can start to constrain the dynamical masses of the quasar host galaxies. If we assume that the gas is located in a rotating, thin disc, we can compute the dynamical masses of the hosts from the observed width and spatial extent of the [C II] emission. We estimate that the dynamical masses of the host galaxies at $z > 6.5$ are $10^{10}\text{–}10^{11}\,M_{\odot}$. If we compare the host galaxy mass to that of the central black hole, we find a ratio that is higher by a factor 3–4 than found locally (Figure 2; Venemans et al., 2016).

We find that the ratio of black hole mass to galaxy mass evolves with redshift as $(1+z)^{0.5\text{–}0.7}$, indicating that black holes grow faster than their host galaxies in the early Universe. This is supported by the relative growth rates; by computing the growth rate of the black holes (derived from the bolometric luminosities of the quasars) and that of the host galaxies (based on the measured star formation rates), we find that, on average, the black holes are growing at least as fast as their host galaxies.

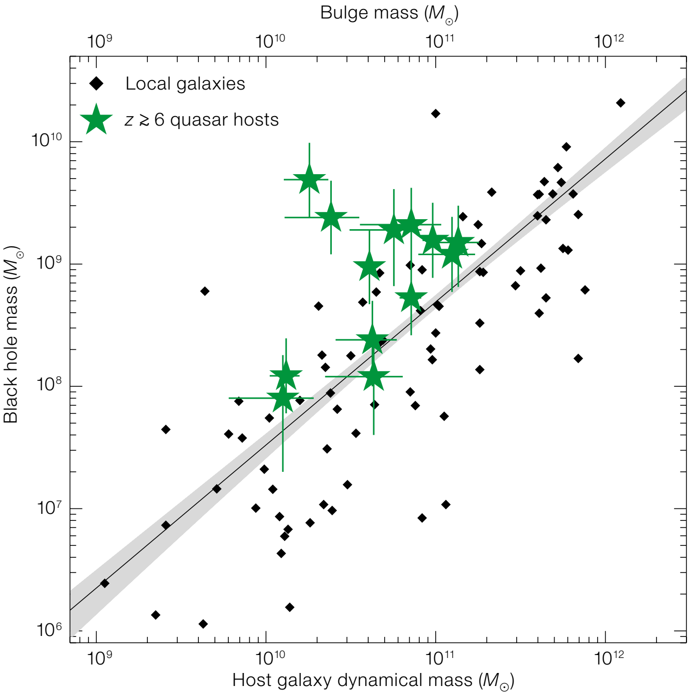

Figure 2. Black hole mass plotted against dynamical mass estimates of $z \geq 6$ quasar host galaxies (filled stars) and the bulge masses of local galaxies (black diamonds, from Kormendy & Ho, 2013). The solid line and grey area show the local black hole to bulge mass relation as derived by Kormendy & Ho (2013). Figure adapted from Venemans et al. (2016).

The crucial assumption in deriving the dynamical masses is that the [C II] emitting gas is distributed in a thin disc. However, our initial observations of the [C II] emission are barely resolved at best. To learn about the spatial distribution and the kinematics of the gas and dust in the quasar host galaxies, higher spatial resolution imaging is essential. We have an ongoing ALMA programme to image the host galaxies of our $z > 6.5$ quasars at high, sub-kiloparsec, resolution (one kiloparsec at $z = 7$ corresponds to an extent of ~ 0.2 arcseconds on the sky). The first source for which we obtained ALMA imaging at a resolution of 1 kiloparsec is the $z = 7.1$ quasar host J1120+0641; the only $z > 7$ quasar known so far.

ALMA high spatial resolution imaging of a $z = 7.1$ quasar host

The host galaxy of the quasar J1120+0641 was initially detected with the PdBI, but the galaxy remained unresolved in the 2 arcsecond beam (~ 10 kpc at the redshift of the quasars; Venemans et al., 2012). As a result, the dynamical mass and the morphology of the line-emitting gas could not be constrained. With ALMA we obtained [C II] imaging at a resolution of 0.23 arcseconds (~ 1 kpc). Surprisingly, the dust continuum and [C II] emission regions are very compact and only marginally resolved in the ALMA data (Figure 3; Venemans et al., 2017a). The majority (80 %) of the emission is associated with a very compact region of size 1.2 × 0.8 square kiloparsecs. Also shown in Figure 3 are the red and blue sides of the emission line: the red contours show emission centred on +265 km s^{-1} and the blue contours the emission centred on −265 km s^{-1}. The red, white and blue crosses indicate the location of the peak of the redshifted, central and blueshifted [C II] emission, respectively. It is clear that there is no evidence for ordered motion at the current resolution.

Applying the virial theorem to these [C II] data yields a dynamical mass for the host galaxy of $(4.3 \pm 0.9) \times 10^{10}\,M_\odot$, only ~ 20 times that of the central supermassive black hole. In the very central region, the dynamical mass of the host is only five times that of the central black hole. In this region, the mass of the black hole and that of the implied dust and gas are able to explain the dynamical mass. In other words, there is not much room for a massive stellar component in the very central region.

The ALMA observations of J1120+0641 begin to spatially resolve the host galaxy of a $z > 7$ quasar. With the even longer baselines available at ALMA, significantly higher-resolution imaging (down to scales of 100s of parsecs) of such distant quasar hosts is now possible, which will start to spatially resolve the sphere of influence of the central supermassive black hole.

The interstellar medium in z ~ 7 quasar host galaxies

By measuring the FIR continuum of the $z > 6.5$ quasar host galaxies at different frequencies and observing additional molecular or atomic lines, we can constrain the physical properties of the interstellar medium (ISM) in these galaxies. We therefore obtained additional millimetre and radio observations with ALMA, the PdBI and the US National Radio Astronomy Observatory (NRAO) Karl G. Jansky Very Large Array (VLA) targeting the CO(2–1), CO(6–5), CO(7–6) and [C I] 370 μm emission lines in the $z > 6.5$ quasar hosts (Venemans et al., 2017a,b). An example of ALMA observations of the CO(6–5), CO(7–6), [C I] and underlying continuum emission in a quasar host at $z = 6.9018$ is shown in Figure 4.

We detected CO emission in all of the $z > 6.5$ quasars we targeted, except for J1120+0641. The [C I] emission line was detected in only one quasar host (Figure 4) and was generally found to be significantly fainter than the [C II] line. The derived [C II]/[C I] luminosity ratio was greater than 13 in all cases. From the CO detections, we can determine the mass of the molecular gas reservoirs. Based on the CO line strength, we estimate that the quasar host galaxies contain a molecular gas mass of $(1\text{–}3) \times 10^{10}\,M_\odot$. This is approximately ten times the mass of the central supermassive black hole. In all quasar hosts, the (limit on the) strength of the CO emission, in comparison to that of [C II], is very similar to the [C II]/CO line ratio measured in local starburst galaxies and star-forming regions in the Milky Way.

Finally, we can compare the [C II]/[C I] and CO/[C II] line ratios to models to

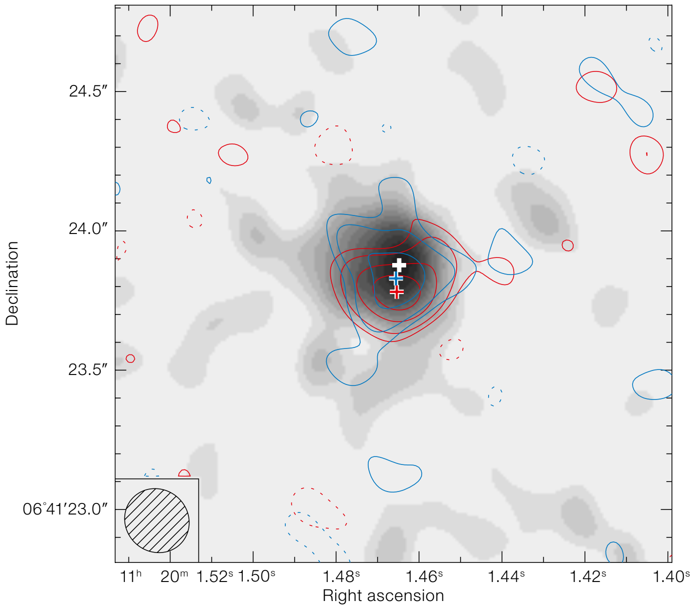

Figure 3. Map of the [C II] emission in J1120+0641 at $z = 7.1$, averaged over the central 265 km s^{-1} (corresponding to 2/3 × the line full width at half maximium), in greyscale. The red and blue contours show emission centred on 256 km s^{-1} and −265 km s^{-1} respectively. The size of the beam (0.23 × 0.22 arcseconds) is shown in the bottom left corner. Figure adapted from Venemans et al. (2017a).

constrain the physical parameters of the emitting gas. For example, the [C II]/[C I] line ratio can be used to determine the dominant source of radiation (Meijerink et al., 2007): ultraviolet radiation from hot, young stars (a photodissociation region, PDR) or hard X-ray radiation from a central, accreting supermassive black hole (an X-ray-dominated region). The measured (limits on the) [C II]/[C I] line ratio in the $z \sim 7$ quasar hosts are inconsistent with excitation by an X-ray dominated region. This implies that the heating in the quasar host galaxies is dominated by star formation, and not by the accreting supermassive black hole (Venemans et al., 2017b).

Our observations of CO and [C I] emission lines have enabled us, for the first time, to characterise the physical properties of the ISM in $z \sim 7$ quasar hosts. By targeting other far-infrared emission lines, such as [O I] 146 μm, [N II] 122 μm, and [O III] 88 μm (all of which are observable with ALMA), we will be able to put further constraints on the properties and metallicity of the interstellar medium in these forming massive galaxies in the early Universe.

Acknowledgements

The work presented here was performed in collaboration with F. Walter, E. Bañados, R. Decarli, E. Farina, C. Ferkinhoff, J. Findlay, P. Hewett, J. Hodge, R. McMahon, R. Meijerink, D. Mortlock, C. Simpson, W. Sutherland, S. Warren, A. Weiß and L. Zschaechner.

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Figure 4. Maps showing (left to right) the CO(6–5), CO(7–6), [CI] 370 μm and continuum emission at an observed wavelength of 3 mm in the host galaxy of quasar J2348-3054 at $z = 6.9018$. These ALMA measurements constitute the highest-redshift CO detections to date. Figure adapted from Venemans et al. (2017b).