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# Star Formation in Quasar Host Galaxies at Redshift 6: Millimeter Surveys and New Insights from ALMA

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**Abstract.** We have been carrying out a systematic survey of the star formation and ISM properties in the host galaxies of z∼6 quasars. Our 250 GHz observations, together with available data from the literature, yield a sample of 14 z∼6 quasars that are bright in millimeter dust continuum emission with estimated FIR luminosities of a few $10^{12}$ to $10^{13}$ $L_\odot$. Most of these millimeter-detected z∼6 quasars have also been detected in molecular CO line emission, indicating molecular gas masses on order of $10^{10}$ $M_\odot$. We have searched for [C II] 158 micron fine structure line emission toward four of the millimeter bright z∼6 quasars with ALMA and all of them have been detected. All these results suggest massive star formation at rates of about 600 to 2000 $M_\odot\,yr^{-1}$ over the central few kpc region of these quasar host galaxies.

**Keywords.** quasars: general — galaxies: starburst — galaxies: evolution — submillimeter

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## 1. Introduction

More than fifty quasars at ∼6 have been detected from large optical and near-infrared surveys, such as the Sloan Digital Sky Survey (hereafter SDSS, e.g., Fan *et al.* 2006) and the Canada-France High redshift Quasar Survey (CFHQS, Willott *et al.* 2007). These objects represent the first generation of supermassive black holes (SMBHs) which formed within 1 Gyr of the Big Bang and are accreting at their Eddington limit (e.g. Kurk *et al.* 2007). Strong millimeter dust continuum, molecular CO, and [C II] 158 $\mu$m fine structure line emission were first detected from the z=6.42 quasar SDSS J114816.64+525150.3 (hereafter J1148+5251, Bertoldi *et al.* 2003a; Maiolino *et al.* 2005, 2012; Walter *et al.* 2003; Riechers *et al.* 2009), indicating intense star formation with a peak surface density of $\sim 1000\,M_\odot\,yr^{-1}\,kpc^{-2}$ over the central 1.5 kpc region (Walter *et al.* 2009). The dynamical mass estimated with the resolved CO line emission indicates SMBH-bulge mass ratios more than one order of magnitude higher than the typical value found in the present universe (Walter *et al.* 2004). The millimeter observations of J1148+5251 suggest an early phase of SMBH-galaxy evolution and the dust continuum, molecular/atomic line emission have been searched in more quasars at the highest redshift (e.g. Carilli *et al.* 2007; Wang *et al.* 2008, 2011a, 2011b; Venemans *et al.* 2012). In this paper, we summarize recent millimeter observations of the sample of quasars known at z∼6 and discuss the star forming activity in these earliest quasar host galaxies.

## 2. Millimeter observations of the z∼6 quasars

A sample of 41 quasars at z∼6 have been observed at 250 GHz using the MAMBO bolometer array on the IRAM 30-m telescope (Bertoldi *et al.* 2003a; Petric *et al.* 2003; Willott *et al.* 2007; Wang *et al.* 2008, 2011a). This 250 GHz observed sample includes all the most luminous (i.e. SDSS z-band magnitudes of $18.74 \leqslant z_{AB} \leqslant 20.42$) objects from the SDSS main survey (e.g. Fan *et al.* 2006) and the objects from the SDSS southern deep imaging survey and the CFHQS (e.g. Jiang *et al.* 2009; Willott *et al.* 2007) that are one to two magnitudes fainter in the optical compared to the SDSS main survey. The MAMBO observations have reached a typical $1\sigma$ sensitivity of $\sim 0.6$ mJy and 14 out of the 41 objects are detected at $\geqslant 3\sigma$, yielding a detection rate of $34 \pm 9\%$. This is consistent with the (sub)mm detection rates of optically selected quasars at redshifts 2 and 4 (Priddey *et al.* 2003; Omont *et al.* 2001, 2003; Carilli *et al.* 2001).

The FIR luminosities estimated with the 250 GHz flux densities for the millimeter-detected z∼6 quasars are a few $10^{12}$ to $10^{13}\,L_\odot$ (Wang *et al.* 2008, 2011). In the left panel of Figure 1, we compare the FIR-to-AGN bolometric luminosity relation of the z∼6 quasars to the local optically selected PG quasars and a sample of IR luminous type I quasars hosted in ultra-luminous infrared galaxies (Hao *et al.* 2005). Most of the millimeter-detected z∼6 quasars follow the shallower luminosity correlation trend defined by the IR quasars (Wang *et al.* 2008, 2011). This may suggest a starburst-dominant FIR emission in the millimeter bright quasars at z∼6, similar to that found in the local IR quasars. We also calculate the average FIR emission by stacking the 250 GHz measurements for the MAMBO non-detections in two quasar luminosity bins (i.e. optically bright, rest-frame 1450 Å AB magnitude $m_{1450} < 20.2$, and optically faint, $m_{1450} \geqslant 20.2$, see Wang *et al.* 2011). The average FIR luminosity/upper limit for the non-detections is consistent with the trend defined by the local PG quasars.

Molecular CO (6-5) line emission has been detected in eleven of the millimeter-detected quasars at z∼6 using the IRAM Plateau de Bure Interferometer (PdBI). The result indicates highly excited molecular gas on order of $10^{10}\,M_\odot$ in the quasar host galaxies (Bertoldi *et al.* 2003b, Riechers *et al.* 2009; Carilli *et al.* 2007; Wang *et al.* 2010, 2011). The FIR and CO luminosities follow the relationship defined by actively star-forming galaxies at low and high redshifts (Riechers *et al.* 2006; Wang *et al.* 2010).

We are also searching for [C II] 158 micron fine structure line emission in our quasar sample. We have an on-going ALMA Cycle 0 program to look for this line in z∼6 quasars with 250 GHz continuum detections (Wang *et al.* 2012, in prep.). The data have been obtained for four of them in the extended configuration with typical resolution of $\sim 0.7''$ and all the four objects show clear detections. The [C II] luminosities are about 1 to $8\times10^9\,L_\odot$ and the [C II]-FIR luminosity ratios are of the order of $10^{-4}$, values that are comparable to those found for other high-z [C II]-detected quasars and about one order of magnitude lower than the typical value of star forming galaxies (e.g. Maiolino *et al.* 2009; Stacey *et al.* 2010; Wagg *et al.* 2012). The line velocity maps of three of them show indications of velocity gradients along the major axis direction. We plot the line intensity and velocity map for one of the detections, ULAS J131911.29+095051.4 at z=6.132 (Mortlock *et al.* 2009), in the right panel of Figure 1. The line emission is

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marginally resolved by the $0.7'' \times 0.5''$ beam, with a deconvolved size of $0.6'' \times 0.3''$ (i.e. 3.5 kpc × 1.7 kpc, fitted to a two-dimensional Gaussian distribution).

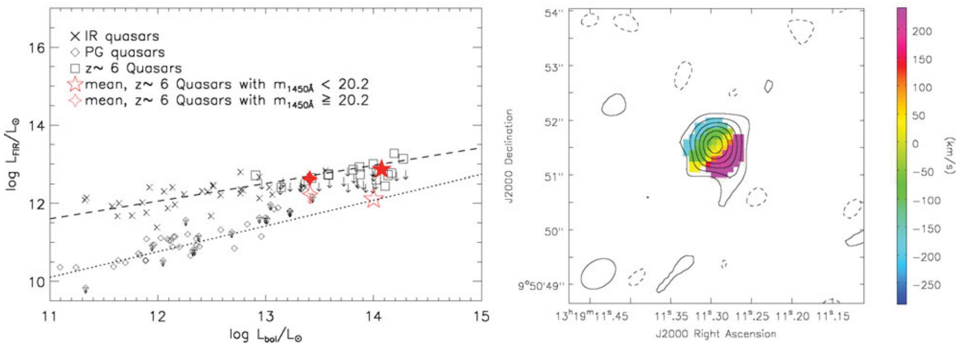


**Figure 1.** Left – The $L_{FIR}$–$L_{bol}$ correlation (Wang *et al.* 2008, 2011). The 250 GHz detected z∼6 quasars are plotted as black open squares and the arrows indicate $3\sigma$ upper limits. The filled four-angle and five-angle stars are the average values for the optically faint ($m_{1450} \geqslant 20.2$) and bright ($m_{1450} < 20.2$) 250 GHz detections, respectively, and the open ones shows the stacking average of the non-detections. The local IR and PG quasars from Hao *et al.* (2005) are plotted as cross and diamonds with arrows denoting upper limits in $L_{FIR}$. The dashed line represent the linear regression of $\log(L_{FIR}) = 0.45\log(L_{bol}) + 6.62$ derived with the local IR quasars and the (sub)mm detected quasars at high redshift (Wang *et al.* 2011), and the dotted line shows the relationship of $\log(L_{FIR}) = 0.66\log(L_{bol}) + 2.8$ from the local PG quasars(Wang *et al.* 2008). Right – ALMA [C II] line velocity-integrated map (contours) and intensity-weighted velocity map (color) of the z=6.132 quasar J1319+0950 (Wang *et al.* 2012, in prep.). The contours are [-2, 2, 3, 4, 6, 8, 10, 12] ×0.18Jy beam$^{-1}$ km s$^{-1}$. The [C II] line emission is marginally resolved by the $0.7'' \times 0.5''$ beam, with a source size of $(0.76 \pm 0.05)'' \times (0.74 \pm 0.04)''$ (deconvolved size of $(0.6 \pm 0.1)'' \times (0.3 \pm 0.2)''$, fitted using the IMFIT package in CASA). The velocity map shows clear velocity gradient along the southwest-northeast direction.

## 3. Discussion: star formation in the millimeter bright z∼6 quasars

The detections of strong dust continuum, molecular CO and [C II] fine structure line emission from the millimeter bright z∼6 quasars strongly suggest active star formation in their host galaxies. In particular, the [C II] detections and the line velocity maps from our ALMA observation suggest a nuclear starburst disk over the central few kpc region. If we conservatively assume that 50% of the FIR emission is powered by host galaxy star formation, the estimated star formation rates (SFR) in the quasar host galaxies are about 600 to 2000 $M_\odot$ yr$^{-1}$ (adopting a standard Salpeter initial mass function, Kennicutt 1998). These together with the molecular gas masses measured from the CO line emission yield gas depletion time scales of $\tau_{dep} = M_{gas}/SFR \sim$ 1–3 $\times 10^7$ yr.

## 4. Summary

We summarize recent millimeter observations of the sample of quasars at z∼6. About 30% of these objects have been detected in strong 250 GHz dust continuum and molecular CO line emission, and our ongoing ALMA observations also detected bright [C II] fine structure line emission in the central few kpc region of the quasar host galaxies. The results suggest massive star formation in the quasar host galaxies, which is in good agreement with the picture of supermassive black hole-galaxy co-evolution at their earliest evolutionary epoch. Further high-resolution imaging of the dust, molecular, and atomic line emission in these objects (e.g. with Cycle 1 and the full configuration of ALMA) will fully probe the gas distribution, star formation rate surface density, star formation efficiency, and dynamical properties of the spheroidal quasar stellar bulges and address the SMBH-bulge relationships and quasar-galaxy evolution at the highest redshift.

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