Millimeter and radio studies of z~6 quasars

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Abstract

We present our recent millimeter and radio study of the SDSS quasars at z~6. The average SED of these quasars is similar to that of the optically selected quasars in the local universe. However, the observational data of strong submillimeter/millimeter ((sub)mm) detections indicate FIR excesses in their SEDs, with estimated FIR luminosities of ~$10^{13}L_{\odot}$. These sources also have FIR to radio ratios consistent with the range defined by star forming galaxies. We discuss the FIR to optical luminosity correlation of the (sub)mm observed optically bright quasars, by including our new observations at z~6, and find this correlation is significantly scattered. Additionally, most of the (sub)mm detected z~6 quasars follow the FIR to optical relationship defined by local IR luminous quasars ($L_{IR}>10^{12}L_{\odot}$). All these facts indicate that the strong (sub)mm detections among the z~6 SDSS quasars are likely due to massive star formation in their host galaxies co-eval with the rapid growth of the central supermassive black hole. Thus they provide ideal candidates to study co-eval black hole and spheroidal galaxy formation in early universe.

Introduction

Many studies suggest that the evolution of SMBHs and their host galaxies are tightly coupled since there are universal relationships between black hole mass and bulge mass/velocity dispersions (eg. Marconi & Hunt 2003; Tremaine et al. 2002; Heckman et al. 2004). These facts raise questions at the highest redshift, suggesting co-eval black hole and spheroidal galaxy formation at the early stages of galaxy evolution.

Observations of the highest redshift quasar, J1148+5251, indicate a huge mass of dust and molecular gas in the host galaxy and suggest active star formation at a rate of ~$10^3 M_{\odot} yr^{-1}$ (eg. Bertoldi et al. 2003; Walter et al. 2004; Beelen et al. 2006).

We are pursuing cm and mm researches of the dust and gas content in the host galaxies of optically selected quasars at z~6. Our goals are to study the general FIR to radio properties of these most distant quasars, and search for co-eval massive star formation with SMBH accretion in the early universe.

Observations and Results

We observed 13 SDSS z~6 quasars with the Very Large Array (VLA) at 1.4GHz. The typical 3σ detection limit of our observation is ~50μJy, which is ten times deeper than the FIRST survey. Six sources were detected with peak flux densities ⩾3σ. We also observed 12 of them with the Max-Planck millimeter bolometer (MAMBO) at 250GHz and mJy sensitivity. Three sources were detected at >3σ, and 1 source is marginally detected with flux density ~3σ.

Analysis

The z~6 quasar sample

There are 19 z~6 quasars that are discovered and published from the SDSS survey (Fan et al. 2006), yielding a complete optically selected quasar sample. Eighteen of them have deep VLA observations and 8 are detected (Petric et al. 2003; Carilli et al. 2004, this work). There are also 18 sources that are observed in (sub)mm at mJy sensitivity with MAMBO/SCUBA (eg. Bertoldi et al. 2003, Priddey et al. 2003b; this work). Eight of them are detected. The detection rate is (44±16)%, which is slightly higher but within errors consistent with the 1/3 (sub)mm detection rate at lower redshifts (eg. Omont et al. 2001; 2003).

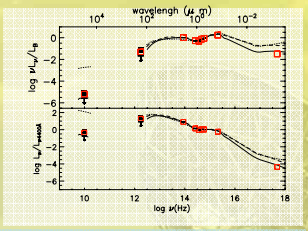


Fig. 1 – Average SED of the z~6 SDSS quasars (red squares). The filled black squares represent the average values of MAMBO and the VLA detections while open black squares denote upper limits.

The Spectral Energy distribution

No remarkable difference is seen between the mean SED of the z~6 SDSS quasars and the local optical quasar templates (Fig. 1, Elvis et al. 1994; Richards et al. 2006). However, more studies on the FIR to submm SEDs of local quasars are needed to make a better comparison.

Strong FIR excess is seen in individual SEDs of strong (sub)mm detections when compared to the local templates. This fact indicates thermal emission from a warm dust component exists in the FIR band of these sources, in addition to the AGN heated hot dust emission. The implied FIR luminosities (L_{FIR}) are ~$10^{13}L_{\odot}$. Additionally, The FIR to radio SEDs of these sources are consistent with that of typical star forming galaxies. Fig. 2 gives two best examples of this case.

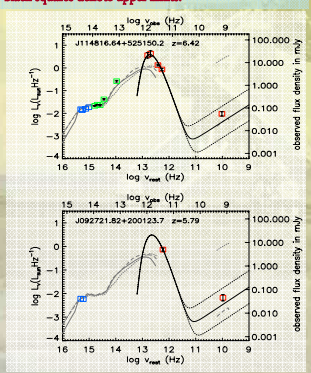
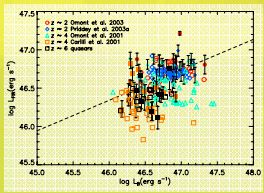


Fig. 2 – SEDs of two (sub)mm detected z~6 SDSS quasars, J1148+5251 and J0927+2001.

Note for Fig. 1 and 2 – The X-ray data are from Brandt et al. (2002), Bechtold et al. (2003), and shemmer et al. (2006). The optical/IR data are from Fan et al. (2003; 2006) and Jiang et al. (2006). The (sub)mm and radio data are from Bertoldi et al. (2003), Robson et al. (2004), Beelen et al. (2006), Carilli et al. (2004), and this work. The thin lines are templates of radio quiet (dashed line) and radio loud (dotted line) quasars from Elvis et al. (1994) and optically luminous quasars from Richards et al. (2006, solid line). The thick solid lines in Fig. 2 are the fitted dust models with T_d=55K/47K and β=1.6 for J1148+5251/J0927+2001. We extend this model FIR emission to the radio band with the typical radio-FIR correlation of a star forming galaxy, i.e. q=2.34 (Yun et al. 2001). The thick dotted lines denote factors of five deviations above and below the typical q value, corresponding to the range observed in star forming galaxies. All the SEDs are normalized to 4400Å.



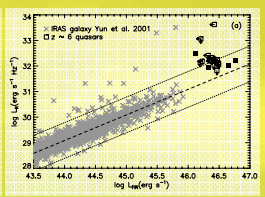


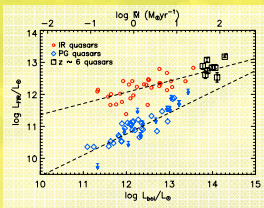
Fig. 3 Left– L_{FIR} vs. L_B for the z~6 quasars and (sub)mm observed quasar samples at lower redshifts. Filled symbols represent detections, while open symbols denote 3σ upper limits. The dashed line is a linear fitting of (sub)mm detections with a slope of 0.40.
Fig. 3 Right – L_R vs. L_{FIR}. The grey crosses are IRAS 2Jy sample of galaxies in Yun et al. (2001) and the dashed line represents the typical correlation of this sample with dotted lines denoting factors of five deviations above and below the typical correlation.

Luminosity correlations

We investigate the FIR to optical luminosity correlation with the z~6 SDSS quasars and other (sub)mm observed optically bright quasar samples at lower redshifts. No correlation is found between L_{FIR} and L_B for the z~6 quasars, but a correlation is present when considering the (sub)mm observed samples at all redshifts (Fig. 3 left). This fact implies the L_{FIR} to L_B correlation is significantly scattered and can only manifests itself with samples spanning a large range in luminosity.

We plot the rest frame 1.4GHz radio luminosity (L_R) vs. L_{FIR} of the z~6 quasars in Fig. 3 (right) and compare them to the IRAS 2Jy galaxy sample (Yun et al. 2001). We found some of the (sub)mm detected z~6 quasars have FIR to radio ratios consistent with the range defined by typical star forming galaxies.

We estimate the bolometric emission (L_{bol}~10.4L_B, Richards et al. 2006) and accretion rate ($\dot{M}$) of the central AGN for the z~6 quasars, and compare the L_{FIR} – L_{bol} correlation of the (sub)mm detections at z~6 to that of local PG quasars and IR luminous quasars (Hao et al. 2005, Fig. 4 left). Most of the (sub)mm detected z~6 quasars seem to favor the L_{FIR} - L_{bol} relationship derived from the local IR luminous quasars with estimated star formation rate (SFR) ~$10^3 M_{\odot} yr^{-1}$. There are two (sub)mm detected quasar at z~6 that have determined black hole masses (Jiang et al. 2006). We find these two sources follow the $SFR/\dot{M} - M_{BH}$ relationship of the local IR quasars (Fig. 4 right).



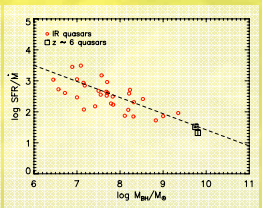


Fig. 4 Left – L_{FIR} vs. L_{bol} of z~6 (sub)mm detected quasars and local PG and IR quasars with arrows denoting upper limits. The dashed lines represent linear fitting results for the PG and IR quasar samples.
Fig. 4 Right – $SFR/\dot{M} - M_{BH}$ for two z~6 (sub)mm detections and the IR quasar sample. The dashed line denotes the linear fitting result from Hao et al. (2005).

Discussion: star forming activity

Is there any evidence for massive star formation in the host galaxies of these z~6 quasars?

- Strong FIR excesses are shown in the individual SEDs of strong (sub)mm detections. The FIR to radio ratios of these sources are consistent with the range defined by star forming galaxies.
- The L_{FIR}-L_B correlation is significantly scattered. This can be understanded if the FIR emission is from starburst heated warm dust. Luminous quasars tend to reside in larger host galaxies, which can lead to a gross correlation between FIR and optical emission.
- Massive star formation is believed to exist in the host galaxies of the IR selected quasars and dominates the FIR emission (Hao et al. 2005). The optical emission of these sources implies rapid SMBH accretion in the center with Eddington ratios ~1. These facts lead to a weak dependence of the FIR emission on the bolometric emission from the central AGN and a decrease of $SFR/\dot{M}$ with increasing black hole mass (Hao et al. 2005). The correlations between FIR emission and AGN activities of the z~6 (sub)mm detected quasars are different from the PG quasars, but similar to the local IR selected quasars.

We do not reach any final answer yet. However, considering the facts above, we suggest massive star formation may be on going in the host galaxies of these (sub)mm luminous quasars at z~6. J1148+5251 presents the first and only well studied example of this case. Similar studies should be done with other strong (sub)mm sources, including observations of submm continuum at higher frequencies and emission lines such as CO and C+.

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