Millimeter and radio studies of $z \sim 6$ quasars

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Abstract

We present our recent millimeter and radio study of the SDSS quasars at $z \sim 6$. The average SED of these quasars is similar to that of the optically selected quasars in the local universe. However, the observational data of these submillimeter (submm) detections indicate FIR excess in their SEDs, with estimated FIR luminosities of $\sim 10^{12} L_{\odot}$. 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 $z \sim 6$, and find this correlation is significantly scattered. Additionally, most of the (sub)mm detected $z \sim 6$ quasars follow the FIR to optical relationship defined by local IR luminous quasars ($L_{\text{IR}} \sim 10^{12} L_{\odot}$). All these facts indicate that the strong (sub)mm detections among the $z \sim 6$ SDSS quasars are likely due to massive star formation in their host galaxies co-evolve with the rapid growth of the central supermassive black hole. Thus they provide ideal candidates to study co-evolve 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; Gabor et al. 2003). Our goals are to study the FIR to optical luminosity correlation of the (sub)mm detections. We evaluate the LFIR-LB correlation of the (sub)mm detected $z \sim 6$ quasars to that of local PG quasars and IR luminous quasars (Hao et al. 2005, Fig. 4 left). Most of the (sub)mm detected $z \sim 6$ quasars seem to favor the $L_{\text{FIR}} \sim L_{\text{B}}$ relationship derived from the local IR luminous quasars with estimated star formation rate (SFR) of $10^{12} M_{\odot} yr^{-1}$. There are two (sub)mm detected quasar at $z \sim 6$ that have determined black hole masses (Jiang et al. 2006). We find these two sources follow the $SFR \sim M_{\text{BH}}$ relationship of the local IR quasars (Fig. 4 right).

Luminosity correlations

We investigate the FIR to optical luminosity correlation with the $z \sim 6$ SDSS quasars and other (sub)mm observed optically bright star forming galaxies. We present the FIR to radio properties of these most distant quasars, and search for co-evolution between the FIR to optical luminosity and the spheroidal galaxy formation.

We estimate the bolometric luminosity ($L_{\text{bol}} = 10^{14} L_{\odot}$, Richards et al. 2006) and accretion rate ($\dot{M}$) of the central AGN for the (sub)mm detected z ~6 quasars, and compare the $L_{\text{FIR}}$ vs. $\dot{M}$ correlation of the (sub)mm detections at $z \sim 6$ to that of local PG quasars and luminous quasars (Hao et al. 2005, Fig. 4 left). 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 $z \sim 6$. 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 frequency and emission lines such as CO and C+.

Observations and Results

We observed 13 SDSS $z \sim 6$ quasars with the Very Large Array (VLA) at 1.4GHz. The 3σ detection limit of our observation is $\sim 50 M_{\odot} yr^{-1}$, which is ten times deeper than the FIRST survey. Six sources were detected with peak flux densities $\geq 3 \sigma$. We observed two of them with the Max-Planck millimeter bolometer (MAMBO) at 250GHz and mJy sensitivity. Three sources were detected at $3\sigma$, and 1 source is marginally detected with flux density $\sim 3\sigma$.

Analysis

The $z \sim 6$ quasar sample

There are 19 $z \sim 6$ quasars that are discovered and published from the SDSS survey (Fan et al. 2006), yielding a completely optically selected 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 sensitivity with MAMBO/SCUBA (eg. Bertoldi et al. 2003, Priddey et al. 2003; 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).

The Spectral Energy Distribution

A remarkable difference is seen between the mean SED of the $z \sim 6$ 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. The implied FIR 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 ($L_{\text{FIR}}$) are $\sim 10^{12} L_{\odot}$. Additionally, The FIR to radio SEDs of these sources are consistent with that of typical star forming galaxies. This gives two best examples of this case.

Discussion: star forming activity

Is there any evidence for massive star formation in the host galaxies of these $z \sim 6$ 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 $L_{\text{FIR}} - L_{\text{B}}$ correlation is significantly scattered. This can be understood 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 $\sim 1$. These facts lead to a weak dependence of the FIR emission on the bolometric emission from the central AGN and a decrease of $SFR \sim M_{\text{BH}}$ with increasing black hole mass (Hao et al. 2005). The correlations between FIR emission and AGN activities of the $z \sim 6$ (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 $z \sim 6$. 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 frequency and emission lines such as CO and C+.