CO Emission Postprint of Dust-Rich Broad Emission Line Quasars

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Abstract

Dusty broad-line quasars are critical to galaxy evolution, and information regarding molecular gas in galaxies aids in understanding their star formation potential and related properties. We observed CO emission lines in nine dusty broad-line quasars at redshifts $0.5 < z < 3$ using the IRAM-30m telescope, successfully detecting nine emission lines at different energy levels in eight sources—five strong detections and four tentative detections. Based on the CO line width-luminosity relation, seven sources are consistent with not being strongly magnified by gravitational lensing, while one source may be magnified by approximately a factor of 12. Far-infrared luminosities were derived from literature values and spectral energy distribution fitting, and corrected for significant gravitational lensing magnification, yielding estimated star formation rates of (40 3 500) M ·a−1 and gas depletion timescales of (20 300) Ma. A comparison between infrared and CO luminosities reveals that the star formation efficiency of this dusty broad-line quasar sample is not significantly different from that of other submillimeter galaxies and quasars. We find a negative correlation between the relative AGN strength and gas depletion time in this sample, consistent with current quasar evolution theories.

Full Text

Preamble

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CO Emission of Dust-Rich Broad-Emission-Line Quasars

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Abstract

Dust-rich broad-emission-line quasars (DBQs) are critical objects in galaxy evolution, and information about molecular gas in these galaxies helps us understand their star-forming potential and other properties. We used the IRAM-30m telescope to observe CO emission lines in nine DBQs at redshifts $0.5 < z < 3$, successfully detecting nine emission lines at different transitions in eight sources. Five lines represent strong detections, while four are tentative detections. Based on the relationship between CO line width and luminosity, seven sources satisfy the relation for objects not strongly magnified by gravitational lensing, while one source may be magnified by approximately 12 times. Using far-infrared luminosities from the literature and spectral energy distribution fitting, and correcting for severe amplification by gravitational lensing, we estimate their star formation rates to be (40–3,500) M yr^{-1} and gas depletion timescales to be (20–300) Myr. Comparing their infrared luminosities with CO luminosities reveals that the star formation efficiency of this DBQ sample shows no significant difference from other submillimeter galaxies and quasars. We find a negative correlation between the relative strength of the active galactic nucleus (AGN) and the gas depletion time in this sample, consistent with current quasar evolution theories.

Keywords: molecular gas; quasars; broad emission lines; gravitational lensing

1 Introduction

Quasi-stellar objects (QSOs) represent a special phase in galaxy evolution where the active galactic nucleus (AGN) reaches extremely high luminosity. The co-evolution of QSOs with their host galaxies constitutes an important topic in galaxy physics. Sanders et al. (1988) proposed that galaxy mergers can produce starburst-dominated ultra-luminous infrared galaxies (ULIRGs, 10^{12} L < LIR < 10^{13} L), which first evolve into dust-obscured quasars. The AGN regulates star formation in the host galaxy through negative feedback such as outflows, leading to a reduction in dust and gas. Unobscured broad-emission-line quasars subsequently form and gradually evolve into quiescent elliptical galaxies. This scenario is supported by observations and hydrodynamic simulations, though many controversies remain. For example, Bournaud et al. (2011) suggested that in high-redshift disk galaxies, inhomogeneities in clumpy material cause inflows that drive the growth of both the central black hole and galaxy-wide star formation activity. In this theoretical framework, the AGN obscuration originates from a thick, dense gaseous disk. Similar to the unified model of quasars, the degree of AGN obscuration in this model depends on the viewing angle.

The discovery of dust-rich broad-emission-line quasars (DBQs) challenges traditional quasar evolution theories. Their infrared luminosities reach the level of luminous infrared galaxies (LIRGs, 10^{11} L $<$ LIR $<$ 10^{12} L) or higher, indicating that the host galaxies contain substantial dust (dust mass ~ 10^{9} M). Simultaneously, they exhibit quasar characteristics with broad emission lines in the optical band, suggesting that the galactic nuclei are largely unobscured by dust along the line of sight. These seemingly contradictory phenomena indicate that the internal matter distribution in DBQs likely differs from known galaxies. For instance, Ivison et al. (2019) proposed that broad-line region features of the AGN may be observed through cavities in the gas and dust. Dust and gas radiation might also primarily reside in spatially close but unresolved companion sources, thus not obscuring the quasar radiation. Similar situations have been found in the WISSH quasar project. Additionally, DBQs are considered a short-lived transitional phase, representing an intermediate stage between dust-rich submillimeter galaxies (SMGs) lacking bright AGN activity and dust-poor broad-emission-line quasars, making them an excellent sample for testing quasar evolution models.

In quasar evolution models, star formation activity represents a crucial manifestation of the co-evolution between quasars and host galaxies. Observations have revealed that quasar star-forming regions are relatively compact with high star formation rate surface densities, differing from the more extended star formation activity in SMGs. However, many methods for measuring star formation properties struggle to exclude other effects, raising questions about their accuracy when applied to DBQs. For example, star formation rates derived from infrared luminosity (LIR) of dust radiation may be contaminated by AGN emission, a degeneracy that requires emission line observations to break, such as Hα, polycyclic aromatic hydrocarbons (PAHs), etc. Molecular gas serves as the raw material for star formation across different phases of the interstellar medium (ISM) and is most directly related to a galaxy’ s ability to form new stars. Carbon monoxide (CO) ranks second only to molecular hydrogen (H_2) in abundance within interstellar molecular gas and requires low excitation temperatures (the first excited state needs only 5 K), making it an excellent tracer of molecular gas. Therefore, CO emission lines provide critical information about a galaxy’ s star-forming potential.

Furthermore, CO emission lines can serve as a diagnostic tool for gravitational lensing effects. Gravitational lensing magnification has been widely discovered in high-redshift surveys, with many objects having ULIRG and hyper-luminous infrared galaxy (HyLIRG, 10^{13} L $<$ LIR $<$ 10^{14} L) luminosities confirmed as strongly lensed. This effect causes objects to have high infrared fluxes, making them easily identified as high-infrared-luminosity galaxies such as DBQs. Therefore, it is necessary to confirm whether selected DBQ sources are severely affected by gravitational lensing. Harris et al. (2012) proposed that in dusty star-forming galaxies (DSFGs), the luminosity of the CO(1-0) emission line has a power-law relationship with its line width. This conclusion was quickly extended to other galaxy types (e.g., SMGs and QSOs at different redshifts) and higher-order CO emission lines. The luminosity of galaxies magnified by foreground objects increases, causing them to deviate from this relationship, with the degree of deviation related to the magnification factor. Rigorous gravitational lens modeling requires high-resolution imaging information to reconstruct the magnification, often necessitating time-consuming millimeter interferometric observations. However, using CO emission line observations, even without resolving the galaxy, the degree of gravitational lensing magnification can be evaluated. By observing CO emission lines in DBQs, we can identify and roughly correct for gravitational lensing effects, initially restoring the true luminosities of DBQs to better determine their star formation rates, dust content, and other properties.

In this paper, we report CO emission line observations of nine DBQs using the IRAM-30m telescope. Section 2 describes the sample selection, observations, and data processing methods. Section 3 presents the observational results, including CO emission line properties and corresponding molecular gas properties. Section 4 discusses the gravitational lensing effects in this sample and analyzes the infrared continuum and star formation properties. Section 5 provides a summary and outlook. Throughout this paper, we adopt the initial mass function from Chabrier (2003) and cosmological parameters from the Planck Collaboration (2018): total matter density $\Omega = 0.315$, dark energy density Ω_Λ = 0.685, and Hubble constant $H_0 = 67.4$ km s^{-1} Mpc^{-2}.

2.1 Sample Selection

The source selection method follows that used by Dai et al. (2012) for DBQ samples. The sample was selected from the 24 m band data of the Spitzer Wide-area InfraRed Extragalactic Survey (SWIRE) using the Multiband Imaging Photometer (MIPS). Selected quasars satisfy 24 m flux S_{24} m > 0.4 mJy (approximately 8σ) and SDSS r-band AB magnitude r_{AB} < 22.5 mag. Spectroscopic data from MMT Hectospec or SDSS confirm them as broad-emission-line quasars, with optical C IV or Mg II line full width at half maximum (FWHM) > 1,000 km s^{-1}. To determine their far-infrared properties, the selected sources were cross-matched with the XID catalog from the Herschel Space Telescope' s HerMES survey. During selection, 24 m observations confirmed no neighboring sources within 18 of each target to prevent contamination from other known sources in SPIRE 250 m photometry. Nine target sources were observed, eight located in the Lockman Hole-SWIRE (LHS) field and one in the XMM-LSS (XMM) field. Most sources have redshifts $0.5 < z < 2$, with only one source at z 3. Relevant information is listed in Table 1 .

Table 1 presents the properties of the sample, including source IDs, coordinates (J2000), near-infrared luminosities, far-infrared luminosities, and infrared luminosities. The table also lists the spectral energy distribution (SED) fitting results from Dai et al. (2012) for sources in the LHS field. Near-infrared luminosity L_{NIR} is obtained by integrating the observed SED over the rest-frame wavelength range 2-10 m. Infrared luminosity L_{IR} is obtained by integrating the observed SED from rest-frame 8 m to observed 24 m, plus integrating the fitted SED from observed 24 m to rest-frame 1,000 m. Far-infrared luminosity L_{FIR} is obtained by integrating the fitted SED over the rest-frame wavelength range 40–300 m. Without correcting for gravitational lensing magnification, the LHS field sample includes two LIRGs (LHS-M066, LHS-M244), one ULIRG (LHS-M235), four HyLIRGs (LHS-S037, LHS-S072, LHS-S119, LHS-S122), and one extremely luminous infrared galaxy (ELIRG, L_{IR} $> 10^{14}$ L) LHS-M104.

2.2 Observations and Data Processing

Between 2011 and 2013, we observed CO emission lines in the selected sample using the IRAM-30m telescope. Observations employed the E090, E150, and E230 bands of the Eight MIxer Receiver (EMIR) frontend, covering the 3 mm, 2 mm, and 1.3 mm atmospheric windows with beam sizes (half power beam width, HPBW) of approximately 29 , 16 , and 11 , respectively. EMIR contains two sidebands (lower sideband, LSB and upper sideband, USB), each 7.44 GHz wide and divided into two equally wide basebands. At the observed frequencies, a single baseband covers a velocity range of approximately 5,000–10,000 km s^{-1}. The backend was the wideband autocorrelator WILMA, consisting of 16 units, each covering 512 channels with 2 MHz spectral resolution, corresponding to a raw velocity resolution of approximately 3-6 km s^{-1}. Since quasars are compact sources, observations used wobbler switching mode. Pointing calibration was performed at least every 2 hours, and focus calibration at least every 4 hours. Table 2 lists the on-source time, observation dates, and observed bands for each source.

Initial observational results were measured in antenna temperature (T*_A) in units of K. We used the point source sensitivity conversion factor S/T*_A from Table 4 of Kramer (1997) to convert antenna temperatures to flux densities (in Jy) for different bands. The resulting spectral data were processed using the CLASS software in GILDAS. We first masked spike noise in individual exposures using windows covering approximately 100 km s^{-1} to ensure complete coverage of spike regions without significantly affecting the spectrum outside the spikes. Signals within these windows were then replaced with random Gaussian noise from a first-order polynomial baseline fit (excluding the window and expected line region). After spike correction, multiple exposures were combined. The combined spectra were first smoothed to a spectral resolution of approximately 60 km s^{-1}, then baseline-subtracted across the entire band excluding the line position. In the spectrum of source XMM-S070, we identified a platforming effect where the baseline showed a clear jump at approximately 163.2 GHz after integration. We fitted and subtracted first-order polynomials to the baselines on each side of the jump separately. For narrower lines, such as the CO(5-4) line in LHS-S072 with FWHM   90 km s^{-1}, a spectral resolution of approximately 30 km s^{-1} was adopted.

For most sources, baseline subtraction used first- or second-order polynomial fits. For the CO(3-2) line in LHS-S037 and the CO(5-4) line in LHS-M104, large-scale fluctuations with frequency 0.003 MHz^{-1} were identified across the entire band using fast Fourier transforms. We estimated the number of zero-crossings and fitted and subtracted fourth- or fifth-order polynomials. High-order polynomial fitting has proven effective for removing baseline periodic fluctuations in single-dish telescope observations. We fitted single Gaussian profiles to the baseline-subtracted emission lines to obtain frequencies, line widths, fluxes, and associated uncertainties.

3.1 CO Emission Lines

We successfully detected CO emission in eight target sources, totaling nine emission line signals. Five signals represent strong detections (signal-to-noise ratio SNR > 5), while four are tentative detections ($3 <$ SNR < 5). In LHS-M104, no CO(3-2) signal with SNR > 3 was detected, but a strong CO(5-4) signal (SNR 6) was found. We assumed the CO(3-2) line width in LHS-M104 matches the CO(5-4) line width (620 km s^{-1}) and used three times the root mean square (RMS) noise of the expected baseband as the flux upper limit. Based on the detected CO(5-4) signal strength and using the quasar conversion factor r_{31} = L *{CO}(1-0)/L* {CO}(3-2) = 0.69 from Carilli & Walter (2013), the expected CO(3-2) integrated flux is S_{CO}ΔV = 1.75 Jy km s^{-1}, with an expected line ratio S_{CO}(3-2)ΔV/S_{CO}(5-4)ΔV = 0.51. This agrees with our estimated flux upper limit (4.75 Jy km s^{-1}) and the corresponding line ratio (1.38). XMM-S070 shows no CO(5-4) signal with SNR > 3; we assumed a line width of 300 km s^{-1} and obtained a 3σ RMS noise upper limit. This width has been used to estimate CO emission line flux upper limits for quasars at similar redshifts (z 1.5). In LHS-S037, both CO(2-1) and CO(3-2) emission lines were detected, with the stronger CO(3-2) line (SNR 6.8) validating the reliability of the weaker CO(2-1) tentative detection (SNR 3.4). Measured line properties are listed in Table 3 , with corresponding spectra shown in Figure 1 [Figure 1: see original paper].

Most sources exhibit line widths of 200–700 km s^{-1} (80%), similar to previously detected CO line widths in quasars. The CO(5-4) line in LHS-S072 shows a relatively narrow width (FWHM $<$ 100 km s^{-1}), which may be related to its gravitational lensing properties. Four CO emission lines show velocity offsets exceeding 3σ from optical spectroscopic redshifts. The CO(2-1) line in LHS-M066 shows a velocity offset of approximately -1,100 km s^{-1} relative to the optical velocity (blueshift relative to the optical redshift frequency is negative). The CO(5-4) line in LHS-M104 shows approximately +2,500 km s^{-1} (redshift relative to the optical redshift frequency is positive). The CO(3-2) line in LHS-M235 shows approximately 400 km s^{-1}, and the CO(4-3) line in LHS-S122 shows approximately 1,000 km s^{-1}. Velocity offsets between CO emission lines and optical redshifts are listed in Table 3, with uncertainties including both CO redshift measurement errors (no lower than spectral resolution) and optical redshift errors (100 km s^{-1}). Shen (2016) found that high-redshift quasar velocities measured through Mg II emission lines typically have uncertainties of 200 km s^{-1}, with a significant fraction (40%) of [O III] flux showing average velocity offsets of 700 km s^{-1}. This may result from relative motion between ionized and molecular gas (such as nuclear outflows), which could account for some of the observed velocity offsets. Velocity offsets exceeding 1,000 km s^{-1} have been observed in other quasars, though their origin remains debated. For example, recoiling black hole models suggest this phenomenon occurs when the black hole powering the quasar forms from a binary black hole merger, releasing gravitational waves that impart velocities of 100-1,000 km s^{-1} relative to the host galaxy, causing displacement from the galactic center. Similar phenomena could also result from dual galactic nuclei, where the quasar-driving black hole experiences gravitational effects from another black hole, producing relative velocity and positional offsets, though theoretical predictions suggest low probability for this scenario (1.5% in binary black hole systems). Additionally, unresolved gas-rich neighboring galaxies at close projected distances around quasars could produce velocity differences between the quasar and gas. The specific origin of these velocity offsets requires confirmation through follow-up observations.

3.2 Molecular Gas Content

We calculated CO emission line luminosities using the formula from Solomon et al. (1997):

$$L'_{\rm CO} = 3.25 \times 10^7 \frac{S_{\rm CO}\Delta V}{\nu_{\rm obs}^2} \frac{D_L^2}{(1+z)^3}$$

where   is the potential gravitational lensing magnification factor, L *{CO} is the CO emission line luminosity (in K km s^{-1} pc^2),* *S*{CO}ΔV is the integrated flux of the emission line (in Jy km s^{-1}), _{obs} is the observed frequency of the emission line (in GHz), D_L is the luminosity distance, and z is the redshift of the emission line (optical redshift and corresponding frequency are used for non-detections). The calculated results are listed in Table 4.

Since the sources appear as quasars in the optical band and SED fitting by Dai et al. (2012) indicates significant AGN contributions in the infrared, we used quasar conversion factors from Carilli & Walter (2013) to convert CO emission line luminosities at different excitation levels to L *{CO}(1-0):* r_{21} *= L* {CO}(2-1)/L *{CO}(1-0) = 0.87,* r_{51} *= L* {CO}(5-4)/L *{CO}(1-0) = 0.97,* r_{41} *= L* {CO}(4-3)/L *{CO}(1-0) = 0.99, and* r_{31} *= L* {CO}(3-2)/L _{CO}(1-0) = 0.69, as shown in Table 4.

Observations indicate that quasar CO emission lines originate from a single component, so we expect the low-excitation luminosities derived from different transitions to be consistent. In LHS-M037, the CO(3-2) and CO(2-1) emission lines indeed yield essentially identical L *{CO}(1-0) values, which validates the accuracy of the conversion factor selection and suggests the source is in an AGN-dominated excitation environment. In LHS-M104, the upper limit from CO(3-2)* *is consistent with the L* {CO}(1-0) value obtained from CO(5-4), indicating our estimated flux upper limit for CO(3-2) is reasonable.

To calculate molecular gas mass M_{mol}, we assume a linear relationship between L *{CO}(1-0) and M*{mol}:

$$M_{\rm mol} = \alpha L'_{\rm CO(1-0)}$$

where the conversion factor $\alpha = 0.8$ M (K km s^{-1} pc^2)$^{-1}$, a value widely applied to quasars at various redshifts. Note that Dunne et al. (2022) give $\alpha = 4.0$ M (K km s^{-1} pc^2)$^{-1}$ for SMGs, which would increase the molecular gas mass by a factor of five. However, since this sample shows clear signs of AGN dominance in both optical and far-infrared bands, the lower conversion factor better describes the CO excitation conditions in the system; we do not consider errors introduced by the conversion factor in subsequent discussions. The calculated M_{mol} values are listed in Table 4. For LHS-S072, which shows evidence of strong gravitational lensing effects, we also provide values corrected for lensing magnification. Most sources with CO detections (75%) have molecular gas masses on the order of 10^{12} M .

4.1 Gravitational Lensing Effects

Accurate measurement of molecular gas mass, star formation rate, and other properties requires knowledge of whether the source brightness is magnified by gravitational lensing. However, lacking imaging observations, we cannot identify signs of gravitational lensing magnification from images. The pointing accuracy (3) and resolution (10 -30 , see Section 2.2) of the IRAM-30m telescope are far below the resolution required to resolve this sample (<1.5 , corresponding to 10 kpc spatial scale at 0.5 < z < 3). Therefore, we employed the diagnostic relationship between CO emission lines to investigate gravitational lensing magnification in this sample. This relationship, first proposed by Harris et al. (2012), has been widely applied to determine whether unresolved sources are strongly magnified by gravitational lensing. Figure 2 [Figure 2: see original paper] plots the CO emission line FWHM (ΔV) on the horizontal axis and the uncorrected CO(1-0) luminosity L _{CO}(1-0) on the vertical axis. The figure includes 200 galaxies from the literature with and without gravitational lensing magnification, along with nine CO emission lines detected in eight sources from this study. For consistency, all literature results were recalculated using the cosmological parameters adopted in this paper (see Section 1).

In this diagnostic diagram, galaxies form two distinct regions. Galaxies not strongly magnified by gravitational lensing (or only slightly magnified) roughly follow a linear relationship in logarithmic coordinates, described by a virial form:

$$L'_{\rm CO(1-0)} = C\left(\frac{\Delta V}{2\sqrt{2\ln 2}}\right)^2 \frac{R}{G\alpha}$$

where R is the radius of the CO emission region (in pc), G is the gravitational constant, and C is a constant related to the galaxy' s kinematics. Galaxies strongly magnified by gravitational lensing have higher luminosities at the same line width and thus lie in the upper-left region. Erb et al. (2006) identified two extreme cases: a disk model with C = 2.1, R = 5, $\alpha = 4.6$, and an ellipsoidal model with C = 5, R = 2, $\alpha = 1.0$. We adopt these as boundaries for galaxies not strongly magnified by gravitational lensing (gray dotted lines in Figure 2), which encompass most unlensed galaxies.

The CO emission lines detected in our sample include both low-excitation ($J \leq 2$) and medium/high-excitation ($J = 3/4$ and $J > 5$) transitions. To confirm the validity of using medium/high-excitation lines for this diagnostic, Figure 2 distinguishes between medium/high-excitation data (solid triangles) and low-excitation data (solid circles). Calculations used the redshift of each emission line and converted the luminosities to L _{CO}(1-0) using conversion factors from Carilli & Walter (2013). The quasar conversion factors match those used in this study (see Section 3.2), while SMGs without obvious AGN activity use: $r_{21} = 0.85$, $r_{31} = 0.66$, $r_{41} = 0.46$, $r_{51} = 0.39$. We find that medium/high-excitation CO lines can also separate galaxies according to gravitational lensing effects, and sources with observations of multiple transitions show that using different excitation levels does not substantially change the conclusion. Note that in LHS-M037, the CO(3-2) line width is larger than the CO(2-1) line width. The low signal-to-noise ratio of the CO(2-1) line introduces large uncertainties in the width measurement. However, if this width is real, the higher-order CO lines may show larger velocity dispersion due to physical processes in the galaxy (such as shocks or outflows), though current observations cannot distinguish this.

Among the eight sources with CO detections, seven lie in the region not strongly affected by gravitational lensing, suggesting their brightness is not significantly magnified (magnification factor 1). Since no CO signal with SNR > 3 was detected in LHS-M104, line width information cannot be provided, and we do not discuss its gravitational lensing magnification here. LHS-S072 lies in the strongly magnified region and is likely severely affected by gravitational lensing. The gray solid line in Figure 2 shows the best-fit relation L *{CO}(1-0) = 5.4*ΔV^2 *from Bothwell et al. (2013), while the gray dashed line shows the best-fit from Harris et al. (2012). Using the CO(1-0) luminosity predicted by the Bothwell et al. (2013) relation as the true luminosity and the ellipsoidal model prediction as the 1*σ *deviation, we calculate a possible magnification factor = 12.2* ± *4.7 for LHS-S072. We use this magnification factor to estimate the true L* {CO}, L *{CO}(1-0), and M*{mol} (see Table 4), as well as infrared luminosity L_{IR} and star formation rate (see Section 4.2 and Table 5). Since LHS-S072 detected the high-excitation CO(5-4) line, the low-excitation line width may be narrower, so the estimated magnification factor may be a lower limit. High-resolution observations are still required to determine the specific magnification of this source and exclude potential gravitational lensing in other sources.

4.2 Infrared Spectral Energy Distribution Properties

For the eight sources in the LHS field, Dai et al. (2012) provided infrared luminosities and other information through SED fitting (see Table 1). To obtain similar information for the XMM field source XMM-S070, we performed SED fitting. The fitting used observational data from the Galaxy Evolution Explorer (GALEX) UV photometry (FUV and NUV bands), XMM-Newton telescope UV photometry (UVW1), SDSS optical photometry (u, g, r, i, z bands), UKIRT Infrared Deep Sky Survey (UKIDSS) near-infrared photometry (J, H, K bands), SWIRE near-infrared data (IRAC instrument at 3.6, 4.5, 5.8, 8.0 m), WISE mid-infrared data (at 3.4, 4.6, 12, 22 m), and Herschel far-infrared data (PACS instrument at 70, 100, 160 m; SPIRE instrument at 250, 350, 500 m).

SED fitting employed the MICHI2 code developed by Liu et al. (2021), which combines physical models with filter response curves to generate panchromatic spectra and performs chi-squared (^{2}) analysis to derive physical parameters. Our fitting models include a stellar component from Bruzual & Charlot (2003), an AGN model from Mullaney et al. (2011), and a dust component in the form of a modified blackbody. In this study, we focus on properties in the infrared band in the rest frame, namely AGN activity and interstellar dust components. Due to large uncertainties introduced by optical band fitting in dust-rich systems, the AGN model was truncated at a rest wavelength of 1 m. In the modified blackbody model, we fixed the emission factor $\beta = 2.0$, consistent with Dai et al. (2012). Considering the lower resolution of SPIRE at 500 m, where flux may be contaminated by other sources, we increased its error to 50% during fitting. The SED and fitting results are shown in Figure 3 [Figure 3: see original paper]. The SED fitting yields uncorrected dust mass M_{dust} = 10^(8.9$±$0.6) M and cold dust temperature T_{dust} = (44 ± 19) K. These dust properties are similar to previously discovered DBQs.

Following the method of Dai et al. (2012), we integrated the observed SED over rest-frame wavelengths 2-10 m to obtain near-infrared luminosity L_{NIR} = 2.4 × 10^{12} L , and integrated the fitted SED over rest-frame wavelengths 40-300 m to obtain far-infrared luminosity L_{FIR} = 3.1 × 10^{12} L . Figure 3 shows that L_{NIR} is primarily contributed by the AGN, while L_{FIR} is mainly contributed by interstellar dust. We integrated the fitted AGN component spectrum from rest-frame wavelengths 1-1,000 m to obtain AGN infrared luminosity L_{IR},AGN = (8.7 ± 0.1) × 10^{12} L , and integrated the fitted dust component spectrum from rest-frame wavelengths 8-1,000 m to obtain starburst infrared luminosity L_{IR},SB = (2.6 ± 1.3) × 10^{12} L . We find that L_{IR},SB does not differ significantly from L_{FIR} (difference $< 1\sigma$).

Figure 4 [Figure 4: see original paper] shows the relationship between far-infrared luminosity and CO emission line luminosity for the nine DBQs in this study. The horizontal axis uses L_{FIR} from Table 1 and L_{IR},SB from Section 4.2 for XMM-S070. The vertical axis uses lensing-corrected L _{CO}(1-0) (see Table 4). The figure also includes 70 QSOs and ULIRGs/SMGs from the literature for comparison. The gray dashed line represents the early universe molecular emission line galaxy (EMG) relation from Solomon & Vanden Bout (2005), including QSOs, ULIRGs, and radio galaxies. Our DBQ sample generally follows this relation, indicating that the star formation efficiency of these dust-rich quasars is similar to previously studied QSOs or SMGs. LHS-M244 deviates significantly above the relation; note that this source also has relatively low AGN strength and high gas depletion time (see Section 4.3), so this deviation may result from relatively higher molecular gas content. The current gas mass upper limit for XMM-S070 cannot determine whether it follows the relation. After correcting for gravitational lensing, LHS-S072 deviates below the relation, possibly due to large uncertainties introduced by the lensing correction. Additionally, LHS-S072 has the highest relative AGN strength (see Section 4.3), so the deviation may also reflect negative AGN feedback on host galaxy star formation.

4.3 Star Formation Properties

To estimate SFRs for DBQs, we used the Chabrier initial mass function and applied a 0.7 correction factor to the conversion formula from Kennicutt (1998), obtaining:

$$\mu\text{SFR}\ (M_\odot\,\text{yr}^{-1}) = 1.2 \times 10^{-10} \mu L_{\text{IR,SB}}\ (L_\odot)$$

We recalculated SFRs for all nine sources using the Chabrier initial mass function and L_{FIR} from Dai et al. (2012), and calculated the SFR for XMM-S070 using L_{IR},SB from Section 4.2. Based on the molecular gas masses from Section 3.2, we calculated gas depletion timescales:

$$t_{\text{dep}} = \frac{M_{\text{mol}}}{\text{SFR}}$$

All results are listed in Table 5 . Most sources with CO detections (75%) have t_{dep} < 60 Myr, significantly shorter than the lifetime of elliptical galaxies (order of 10 Gyr), demonstrating that DBQs represent a brief evolutionary transition phase. This timescale is also shorter than typical quasar lifetimes (order of 100 Myr), meaning that after the DBQ phase, galaxies will evolve into quiescent quasars unless the initial mass function differs significantly from Chabrier (2003) or star formation receives external gas replenishment. Previous infrared and millimeter observations found that only 20%-30% of quasars coexist with high-infrared-luminosity starburst galaxies, indicating that the DBQ phase represents a low fraction of quasar evolution, consistent with the relatively short timescales we observe for DBQs.

To explore the relationship between AGN and star formation activity, we defined the relative AGN strength in the galaxy as f_{AGN} = L_{NIR}/(L_{FIR} + L_{NIR}), with results listed in Table 5. f_{AGN} shows a negative correlation with t_{dep} (see Figure 5 [Figure 5: see original paper]), indicating that AGN activity is positively correlated with star formation efficiency. We performed a least-squares fit to the eight sources with CO detections:

$$\log(t_{\mathrm{dep}}) = -2.6(\pm1.1) \times f_{\mathrm{AGN}} + 2.7(\pm0.4)$$

where t_{dep} is in units of Myr.

Numerous survey studies show that AGN accretion rates and star formation rates both peak at redshift 2, indicating a coeval relationship between AGN and star formation. In the cold flow model proposed by Bournaud et al. (2011), cold gas flows simultaneously promote star formation and AGN activity, so the positive correlation between AGN activity and star formation efficiency is consistent with this model. More samples are needed in the future to confirm this relationship and provide better constraints.

5 Summary and Outlook

We observed CO emission lines in nine dust-rich broad-emission-line quasars using the IRAM-30m telescope. Nine signals with SNR > 3 were detected in eight target sources, including five strong detections (SNR > 5) and four tentative detections (3 < SNR < 5).

CO line widths are approximately (200–700) km s^{-1}. Four emission lines show velocity offsets from optical redshifts of (400–2,500) km s^{-1}, possibly caused by internal motions or companion sources. Using quasar conversion factors, we obtained L *{CO}(1-0) on the order of 10^{10} K km s^{-1} pc^{2}, corresponding to molecular gas masses M*{mol} on the order of 10^{10} M .

Using the CO line width versus luminosity relationship, we estimate that seven sources are not strongly magnified by gravitational lensing, so their luminosities represent true values. Source LHS-S072 may be strongly lensed with magnification factor 12.

We performed SED fitting for XMM-S070 and combined it with infrared information for other sources from the literature, finding that the lensing-corrected infrared luminosities of this DBQ sample indicate they are LIRGs or above. They generally follow the EMG far-infrared luminosity versus CO luminosity relationship, suggesting that the star formation efficiency of this DBQ sample shows no significant difference compared to starburst galaxies with less dust or weaker AGN activity.

Assuming a Chabrier initial mass function, we estimate star formation rates for this sample to be on the order of 10–1,000 M yr^{-1}. Most sources have gas depletion timescales < 60 Myr, indicating that DBQs represent a brief phase in quasar evolution. We find a positive correlation between relative AGN strength and star formation efficiency, though this relationship requires further observational confirmation.

The DBQ sample in this study provides an important sample for understanding galaxy evolution from dust-rich systems to quasars. After correcting for gravitational lensing magnification through CO emission line observations, we demonstrate that they represent a short-lived transitional evolutionary phase. During the DBQ phase, AGN may promote star formation in the host galaxy, which is significant for studying the co-evolution of AGN and host galaxies. Future high-resolution observations are still needed to resolve the interstellar medium distribution in these sources and exclude possible gravitational lensing effects. Similar observations need to be expanded to larger samples to better determine the relationship between AGN and star formation.

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