The evolutionary connection between QSOs and SMGs: molecular gas in far-infrared luminous QSOs at $z \sim 2.5$

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ABSTRACT
We present IRAM Plateau de Bure Interferometer observations of the $^{12}$CO (3–2) emission from two far-infrared luminous QSOs at $z \sim 2.5$ selected from the Herschel-ATLAS survey. These far-infrared bright QSOs were selected to have supermassive black holes (SMBHs) with masses similar to those thought to reside in sub-millimetre galaxies (SMGs) at $z \sim 2.5$; making them ideal candidates as systems in transition from an ultraluminous infrared galaxy phase to a sub-mm faint, unobscured, QSO. We detect $^{12}$CO (3–2) emission from both QSOs and we compare their baryonic, dynamical and SMBH masses to those of SMGs at the same epoch. We find that these far-infrared bright QSOs have similar dynamical but lower gas masses than SMGs. In particular we find that far-infrared bright QSOs have $\sim 50 \pm 23\%$ less warm/dense gas than SMGs, which combined with previous results showing the QSOs lack the extended, cool reservoir of gas seen in SMGs, suggests that they are at a different evolutionary stage. This is consistent with the hypothesis that far-infrared bright QSOs represent a short ($\sim 1$ Myr) but ubiquitous phase in the transformation of dust obscured, gas-rich, starburst-dominated SMGs into unobscured, gas-poor, QSOs.

Key words: galaxies: formation, — galaxies: evolution — quasars: emission lines — quasars: individual — J0908-0034, J0911+0027
1 INTRODUCTION

An evolutionary link between local ultraluminous infrared galaxies (ULIRGs, with far-infrared [FIR] luminosities of $L_{\text{FIR}} \geq 10^{12} L_{\odot}$) and QSOs was first suggested by Sanders et al. (1988) and considerable effort has been expended to test this connection in the local Universe (e.g. Tacconi et al. 2002; Veilleux et al. 2009). This hypothesis has been strengthened by the discovery of a relation between the mass of supermassive black holes (SMBHs) and the mass of their host spheroids (e.g. Magorrian et al. 1998; Gebhardt et al. 2000; Ferrarese & Merritt 2000), which suggests a physical connection between the growth of spheroids and their SMBHs. As shown by theoretical simulations, such a link can be formed through the suppression of star formation in a host galaxy by winds and outflows from an active galactic nucleus (AGN) at its centre (Di Matteo et al. 2005; Hopkins et al. 2005).

Both the ULIRG and QSO populations evolve very rapidly with redshift, and although subject to selection biases, intriguingly both populations appear to reach a broad peak in their activity at $z \sim 2.5$ (Shaver 1983; Chapman et al. 2003; Wardlow et al. 2011). The high-redshift ULIRGs, which are typically bright at sub-millimetre wavelengths, and hence are called sub-millimetre galaxies (SMGs), are thought to represent the formation of massive stellar systems through an intense burst of star formation in the early Universe, triggered by mergers of gas-rich progenitors (Frayre et al. 1998; Blain et al. 2002; Swinbank et al. 2006, 2010a; Tacconi et al. 2006; 2008; Engel et al. 2010).

The similarity in the redshift distribution of the SMGs and QSOs may be indicating that the evolutionary link between these populations, which has been postulated locally, also holds at $z \sim 2$, when both populations were much more numerous, and significant in terms of stellar mass assembly. Indeed recent work on the clustering of $z \sim 2$ QSOs and SMGs has shown that both populations reside in parent halos of a similar mass, $M_{\text{halo}} \sim 10^{13} M_{\odot}$ (Hickox et al. 2012), adding another circumstantial connection between them. Moreover, the characteristic $M_{\text{halo}}$ is similar to the mass at which galaxy populations transition from star forming to passive systems (e.g. Brown et al. 2008; Coil et al. 2008; Hartley et al. 2010) which may be indirect evidence for the influence of QSO-feedback on star formation in galaxies (Granato et al. 2001; Lapi et al. 2006). One other piece of circumstantial evidence for a link between SMGs and QSOs comes from estimates of the masses of SMBHs in SMGs. Due to the dusty nature of SMGs these studies are inherently challenging, yielding results with more scatter than seen for optical quasars. However, they suggest that the SMBH masses are $\sim 10^8 M_{\odot}$, significantly lower than seen in comparably massive galaxies at the present-day (Alexander et al. 2008). This indicates the need for a subsequent phase of SMBH growth, which could be associated with a QSO phase.

One puzzling issue about the proposed evolutionary connection between high-redshift QSOs and SMGs is only a small fraction of sub-millimetre detected galaxies ($S_{22} \geq 5\text{mJy}$), are identified as optically-luminous, $M_B \leq -22$, $z \sim 1-3$ QSOs ($\sim 2\%$, Chapman et al. 2003; Wardlow et al. 2011), indicating that, if they are related, then the QSO and ULIRG phases do not overlap significantly. Taken together, these various results provide support for an evolutionary link between high-redshift ULIRGs (SMGs) and QSOs, with a fast transition ($\sim 1\text{Myr}$) from the star-formation-dominated SMG-phase to the AGN-dominated QSO-phase (e.g. Page et al. 2012), where rapid SMBH growth can then subsequently account for the present-day relation between spheroid and SMBH masses. In this scenario, when a QSO is detected in the far-infrared/sub-millimetre it will be in the transition phase from an SMG to an unobscured QSO, making its physical properties (e.g. gas mass, dynamics, etc.) a powerful probe of the proposed evolutionary cycle (e.g. Page et al. 2004, 2011; Stevens et al. 2005).

In this paper we present a study with the IRAM Plateau de Bure interferometer (PdBI) of the cold molecular gas in far-infrared-selected “transition” candidate QSOs from the Herschel-H-ATLAS survey (Eales et al. 2010). We detect $^{12}\text{CO}$ (3–2) in both far-infrared bright QSOs studied, and compare the gas and kinematic properties of these to other $^{12}\text{CO}$-detected QSOs and SMGs to relate their evolution. Throughout we adopt cosmological parameters from Spergel et al. (2003) of: $\Omega_m = 0.27$, $\Omega_{\Lambda} = 0.73$ and $H_0 = 71\text{ km s}^{-1}\text{ Mpc}^{-1}$.

1 QSO, quasi-stellar object, defined as having $M_B \leq -22$ and one or more broad emission lines with a width $\geq 1000 \text{ km s}^{-1}$.

2 Herschel is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.
Molecular gas in FIR-luminous QSOs at \(z \sim 2.5\)

**Figure 2.** Upper: The velocity-integrated \(^{12}\)CO (3–2) emission for the two QSOs (summed over the regions marked in the spectra below). The contours represent signal-to-noise, and are spaced at \(\pm 3, 4, 5, \ldots \times \sigma\) (dashed contours are negative). Significant \(^{12}\)CO (3–2) emission is detected from both QSOs and is well-centered on the optical positions of the QSOs, indicated by a cross (offset by \(1–2''\), which is within the primary beam). Analysis of the channel maps shows both sources are unresolved with no evidence of velocity gradients, although the modest spatial resolution of our maps means that this is not a strong constraint. Lower: Spectra showing the redshifted \(^{12}\)CO (3–2) emission lines from both QSOs. The spectra were binned to a resolution of 10 MHz and 20 MHz respectively, and we overlay the best fitting Gaussian plus continuum model (the continuum emission in both QSOs is negligible). The redshift derived from \(^{12}\)CO (3–2) as well as the line flux and line widths derived from the Gaussian fits are reported in Table 2. We note that the FWHM of the J0908$-$0034 emission line is relatively narrow, at \(125 \pm 25 \text{ km s}^{-1}\), compared to \(530 \pm 100 \text{ km s}^{-1}\) for J0911+0027. In each spectrum the predicted position of the \(^{12}\)CO (3–2) emission line, from the 2SLAQ UV spectrum, is indicated by an arrow. The two dot-dashed lines correspond to \(\pm \text{FWHM}\), and show the region which was summed to produce the maps above.

2 OBSERVATIONS & DATA REDUCTION

2.1 Sample Selection

Our aim is to study the molecular gas and dynamical properties of far-infrared bright QSOs to test their evolutionary link to SMGs, for which larger samples are now available (Greve et al. 2005; Bothwell et al. 2012). We focus our study on potential transition (far-infrared bright) QSOs at the era when the activity in both the QSO and SMG populations peaked, \(z \sim 2.5\). Previous \(^{12}\)CO studies of unlensed far-infrared or sub-millimetre-bright QSOs (Coppin et al. 2008) have usually studied the most luminous QSOs, with SMBH masses \(\geq 2\) orders of magnitude larger than those seen in typical SMGs and correspondingly low space densities. Both of these factors make it hard to relate the properties of these extreme QSOs to typical SMGs (studies of lensed QSO samples, Riechers 2011, suffer from the difficulty of determining the true space densities of the sources being studied). The limitations of these previous studies arose because of the lack of large samples of far-infrared/sub-millimetre detected QSOs; (Coppin et al. 2008) selected a sample of QSOs which were later found to be bright in the sub-mm. But with the advent of wide-field far-infrared/sub-millimetre surveys with the Herschel Space Observatory (Pilbratt et al. 2010) we can now select samples of QSOs with redshifts, space densities, far-infrared luminosities and most critically SMBH masses which are well-matched to those of the hypothesised descendents of typical SMGs.

For our analysis we have therefore used the sample of far-infrared observed QSOs from Bonfield et al. (2011) which are derived from the survey of the 9° H-ATLAS field (Eales et al. 2010). Bonfield et al. (2011) extracted far-infrared fluxes from the SPIRE 250, 350 and 500-\(\mu\)m maps (Griffin et al. 2010; Pascale et al. 2011) at the optical position of 372 QSOs from either SDSS (Schneider et al. 2010) or 2SLAQ (Croom et al. 2009) surveys across the \(\sim 16\) degree²
field. A statistical background subtraction was performed on the measured fluxes for each QSO to account for confusion in the maps, see [Bonfield et al. (2011)]. Of the 372 QSOs, ∼ 20% are consistent with having L_{FIR} ≥ 10^{12} L_⊙, making them candidates for “transition” QSOs (e.g. between a far-infrared bright SMG and far-infrared faint unobscured QSO phase). Restricting the redshift range to z = 2–3 (to roughly match the redshift peak of SMGs, Chapman et al. 2005), gives 29 QSOs. We then estimated SMBH masses for these QSOs from the extrapolated rest frame 5100-Å luminosities (e.g. Wandel et al. 1999) to select those with SMBH masses of M_{BH} ≤ 3 × 10^8 M_⊙, comparable to SMGs {Alexander et al. 2008}. These selection criteria resulted in nine targets and from this list we selected six QSOs for a pilot project to determine their gas masses and dynamics through the detection of 12CO (3–2) emission with PdBI. We estimated systemic redshifts for these QSOs using the measured wavelengths from Gaussian fits to the Si\textsc{iv} (1996) emission lines and their rest frame 1350-Å emission. There may be a relation between far-infrared luminosity and weak Ly\textalpha emission. There may be a relation between far-infrared luminosity and weak Ly\textalpha, but its physical origin is still unknown.

This paper presents the PdBI observations of the first two QSOs from this sample: J0908−0034 (RA: 09 08 47.18, Dec: −00 34 17.9, J2000: z_{UV} = 2.5073) and J0911+0027 (RA: 09 11 48.38, Dec: +00 27 19.7, J2000, z_{UV} = 2.3697).

### 2.2 PdBI Observations

We used the six-element IRAM PdBI in compact (D) configuration to search for redshifted 12CO (3–2) emission from the QSOs. We tuned the correlator WideX to the frequency of redshifted 12CO (3–2) from the estimated redshifts derived from their UV emission lines (Fig. 1). We then adjust our estimates by the weighted mean velocity offsets of these lines from 12CO (3–2), for the 12CO-detected QSOs in Coppin et al. (2008) (we find Siv1397 provides the best estimate of the systemic redshifts). We note that, as previously seen by Omont et al. (1990), roughly ∼ 80% of these far-infrared bright QSOs show very weak Ly\textalpha emission. There may be a relation between far-infrared luminosity and weak Ly\textalpha, but its physical origin is still unknown.

| QSO         | α_{CO} (J2000) | δ_{CO} (J2000) | S_{250\mu m} a (mJy) | S_{350\mu m} a (mJy) | S_{500\mu m} a (mJy) | S_{3\text{mm}} (mJy) |
|-------------|----------------|---------------|----------------------|----------------------|----------------------|---------------------|
| J0908−0034  | 09 08 47.18    | −00 34 17.6   | 9.0 ± 6.6            | 26.2 ± 8.1           | 15.0 ± 9.0           | < 1.4               |
| J0911+0027  | 09 11 48.30    | +00 27 18.4   | 23.5 ± 5.8           | 14.7 ± 6.6           | 7.7 ± 7.8            | < 1.0               |


### Table 1: Observed Properties

*a J0908−0034 flux density values are after deblending sources. Fluxes extracted at the optical position of the QSO, before deblending, are 15.6 ± 6.4 mJy, 39.5 ± 7.1 mJy and 41.0 ± 8.5 mJy.

### 2.3 Far-infrared Luminosities and SMBH Masses

For our analysis we require more accurate estimates of the far-infrared luminosities and SMBH masses of our QSOs. To estimate far-infrared luminosities of the QSOs in our sample, we exploit the Herschel SPIRE 250, 350 and 500-μm imaging. For each QSO, we deblend multiple sources in the vicinity, using the 250-μm map to identify nearby sources. For J0911+0027 there is a bright 250μm source centered at the optical position of the QSO which is clearly isolated, but J0908−0034 has significant (40%–60%) at 250–500μm contamination from a galaxy ∼30′′ away. We report the final deblended photometry for each source in Table 1. To derive the far-infrared luminosity for each QSO, we fit a modified black body spectra to the SPIRE photometry, adopting a dust emissivity, β = 1.6 and fixing the temperature of the modified black body at T_d = 40 K. (the average dust temperature of z ∼ 2–3 QSOs, Beelen et al. 2006.) and calculate the far-infrared luminosity (L_{FIR}) by integrating the best-fit SED between (rest-frame) 8–1000 μm. We note that if we instead allow the characteristic dust temperature to vary in the SED fit, we see at most a ∼45% change in L_{FIR}, consistent within our error estimates. The modified black body fits confirm the L_{FIR} for both QSOs is ≈ (3 - 4 ± 1) × 10^{12} L_⊙ (Table 2). The QSOs are thus significantly fainter in the FIR than the QSO sample of Coppin et al. (2008), L_{FIR} = (7.5 ± 1.5) × 10^{12} L_⊙, and also at the fainter end of the SMGs in Bothwell et al. (2012), L_{FIR} = (4.8 ± 0.6) × 10^{12} L_⊙. The implied star-formation rate (SFR) are 500–700 M_⊙ yr^{-1}.

We calculated SMBH masses for both QSOs from the FWHM of their CIV 1549 emission lines and their rest frame 1350-Å continuum luminosities (L_{1350}), following Eq. 7 from Vestergaard & Peterson (2006). This relation is calibrated to the results of reverberation mapping, however the geometry of the broad line region (producing the emission lines) is poorly constrained and may bias virial mass estimates to low values (Jarvis & McLure 2006; Fine et al. 2011). We derive the FWHM from a Gaussian fit to the...
Molecular gas in FIR-luminous QSOs at z ∼ 2.5

3 ANALYSIS & RESULTS

We detect $^{12}$CO emission near the optical position of each QSO (offset by 1–2'' and at frequencies close to those expected for redshifted $^{12}$CO (3–2). For each QSO, we fit a combination of a Gaussian and a uniform continuum to the spectrum corresponding to the peak signal-to-noise, $S/N$, pixel in each map and report the resulting redshift, line width and line flux in Table 2, as well as overplotting the fit on Fig. 2. We do not see strong evidence of reddening in the 2SLAQ spectrum of any QSO (as measured from the g-band SDSS magnitudes of $g = 21.41 ± 0.05$ for J0908−0034 and $g = 21.64 ± 0.05$ for J0911+0027). As we do not see any significant continuum is detected in either source. We now discuss the SMBH masses of $∼ 2 \times 10^9 M_\odot$ for both QSOs (Table 2). We caution that estimates from the C iv emission line in the 2SLAQ spectrum (Fig. 1), measuring $\Delta v = 1$–2'', may be overestimated.

We collapse the spectral cube over the frequency range corresponding to $\pm 500 \text{ km s}^{-1}$ for J0908−0034 and J0911+0027, respectively (Table 2). From the peak of the Gaussian distribution, we determine a $^{12}$CO redshift of $z = 2.5008 ± 0.0002$. We compared $z_{\text{CO}}$ with the wavelength of emission lines in the 2SLAQ spectrum of this QSO (Fig. 1). We found the UV lines to be blue-shifted by $\Delta v ≈ 100–500 \text{ km s}^{-1}$, relative to $z_{\text{CO}}$, with Lyα and NV emission lines having the largest offset. Systematic offsets of UV emission lines are not unusual, and are usually attributed to resonant scattering of the emission line, due to material in the line of sight to the AGN (Steidel et al. 2010). At the spatial resolution of our D-configuration PdBI observations we do not find any evidence for spatially resolved $^{12}$CO (3–2) emission, and channel maps show no sign of a velocity gradient across the source.

$J0911+0027$ — The integrated $^{12}$CO emission is detected at a significance of 7.2σ. The $^{12}$CO (3–2) spectrum is binned to a frequency resolution of 20 MHz ($\sim 60 \text{ km s}^{-1}$), as shown in Fig. 2. We find the $^{12}$CO (3–2) emission line to be well fitted by a single Gaussian with FWHM $= 125 ± 25 \text{ km s}^{-1}$, and a velocity-integrated flux of $S_{\text{CO}} \Delta v = 0.23 ± 0.05 \text{ Jy km s}^{-1}$; see Table 2. From the peak of the Gaussian distribution, we determine a $^{12}$CO redshift of $z = 2.5008 ± 0.0002$. We compared $z_{\text{CO}}$ with the wavelength of emission lines in the 2SLAQ spectrum of this QSO (Fig. 1). We found the UV lines to be blue-shifted by $\Delta v ≈ 100–500 \text{ km s}^{-1}$, relative to $z_{\text{CO}}$, with Lyα and NV emission lines having the largest offset. Systematic offsets of UV emission lines are not unusual, and are usually attributed to resonant scattering of the emission line, due to material in the line of sight to the AGN (Steidel et al. 2010). At the spatial resolution of our D-configuration PdBI observations we do not find any evidence for spatially resolved $^{12}$CO (3–2) emission, and channel maps show no sign of a velocity gradient across the source. We now compare our observations of these two far-infrared-luminous, but otherwise fairly typical, QSOs with the more luminous (and more massive) far-infrared bright QSOs previously studied, as well as with the SMG population. In particular, we investigate what the observed properties of our QSOs can tell us about their relationship to SMGs.

3.1 Gas Mass

The $^{12}$CO (3–2) line emission from each QSO provides information about the molecular gas mass of the system (Solomon et al. 1997). We determine the $^{12}$CO (3–2) line luminosity, $L_{\text{CO}}^{3-2}$, following Eq. 3 from Solomon & Vanden Bout (2002), deriving $L_{\text{CO}}^{3-2} = (0.77 ± 0.15) \times 10^{10} \text{ K km s}^{-1} \text{ pc}^2$ and $L_{\text{CO}}^{3-2} = (1.87 ± 0.33) \times 10^{10} \text{ K km s}^{-1} \text{ pc}^2$ for J0908−0034 and J0911+0027 respectively (Table 2).

Table 2: Physical Properties

| Source   | $z_{\text{CO}}$ | $S_{\text{CO}} \Delta v$ (Jy km s$^{-1}$) | FWHM$_{\text{CO}}$ (km s$^{-1}$) | $L_{\text{CO}}^{3-2}$ (10$^{12}$ L$_\odot$) | $L_{\text{FIR}}$ (10$^{10}$ L$_\odot$) | $M_{\text{gas}}$ (10$^8$ M$_\odot$) | $M_{\text{BH}}$ (10$^8$ M$_\odot$) |
|----------|-----------------|------------------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| J0908−0034 | 2.5008 ± 0.0002 | 0.23 ± 0.04 | 125 ± 25 | 0.77 ± 0.15 | 3.1 ± 0.8 | 0.77 ± 0.15 | 1.6$^{+9.3}_{-1.4}$ |
| J0911+0027 | 2.3723 ± 0.0005 | 0.62 ± 0.10 | 530 ± 100 | 1.87 ± 0.33 | 3.5 ± 0.8 | 1.9 ± 0.3 | 2.5$^{+1.4}_{-0.9}$ |

4 We estimate errors by bootstrap resampling the 2SLAQ spectrum, with replacement, and re-fitting a Gaussian model.
To estimate the total masses of the gas reservoirs in these QSOs we use the $^{12}\text{CO} (3-2)$ luminosity to estimate the expected $^{12}\text{CO} (1-0)$ luminosity and from that estimate the total gas mass. For the first step we use the results from Riechers et al. (2011) and assume a typical line brightness temperature ratio, for the gas in QSOs, of $r_{31} = L'_{\text{CO}(3-2)}/L'_{\text{CO}(1-0)} \sim 1$ (i.e. thermalised gas) to convert the $^{12}\text{CO}(3-2)$ line luminosities of our QSOs, and the Coppen et al. (2008) sample, to $^{12}\text{CO} (1-0)$ luminosities. We caution that we are extrapolating the results of Riechers et al. (2011) to our sample of QSOs, and that in AGN dominated systems super-thermal ratios, i.e. $r > 1$, are not uncommon (e.g. Papadopoulos et al. 2008; Ivison et al. 2012). We then adopt a CO-to-H$_2$ conversion factor of $\alpha = 1 \text{ M}_\odot (K \text{ km s}^{-1} \text{pc}^2)^{-1}$ following Bothwell et al. (2012) to convert $L'_{\text{CO}} (1-0)$ to the give gas masses (Table 2). Note that $\alpha$ is denoted as a conversion to H$_2$, but the resulting H$_2$ mass is defined as the total H$_2$+He gas mass. In this manner we derive gas masses of $M_{\text{gas}} = (0.77 \pm 0.15) \times 10^{10} \text{ M}_\odot$ and $M_{\text{gas}} = (1.9 \pm 0.3) \times 10^{10} \text{ M}_\odot$ for J0908–0034 and J0911+0027 respectively.

The gas masses of our far-infrared luminous QSOs are lower than the median gas mass of the extremely far-infrared luminous QSOs detected by Coppen et al. (2008), $M_{\text{gas}} = (4.3 \pm 1.0) \times 10^{10} \text{ M}_\odot$, and they are also lower than the median gas mass of SMGs from Bothwell et al. (2012), $M_{\text{gas}} = (5.3 \pm 1.0) \times 10^{10} \text{ M}_\odot$. We note that there is significant scatter around these averages, and the larger of our QSO gas masses is consistent within 3-$\sigma$. To allow a fair comparison, we have transformed the literature estimates of $M_{\text{gas}}$ to use $\alpha = 1$. We also note that the bulk of the observations come from $^{12}\text{CO}(3-2)$, although Bothwell et al. (2012) use $r_{31} = 0.52 \pm 0.09$ in their conversion of $L'_{\text{CO}(3-2)}$ to $L'_{\text{CO}(1-0)}$ which is appropriate for SMGs due to the presence of an extended reservoir of cold gas. As we will discuss in Fig. 3 the lower gas masses we derive for our far-infrared QSOs are consistent with them having recently evolved from a previous-SMG phase.

### 3.2 Gas Fraction

One crude measure of the evolutionary state of a system is the fractional contribution of molecular gas to its total mass. Hence, in the absence of significant replenishment of gas from external sources, we would expect the gas-mass fraction in SMGs to decline as they evolve, and thus in the evolutionary model we are testing, our QSOs ought to have lower gas-mass fractions than SMGs.

In Fig. 3 we use a combination of observables which trace gas mass, $L'_{\text{CO}(3-2)}$, and dynamical mass, $FWHM^2/\sin^2i$, as a proxy for gas-mass fraction, $L'_{\text{CO}(3-2)} \sin^2i/\text{FWHM}^2$. In choosing this proxy we make two implicit assumptions: (i) that the gas reservoir in both SMGs and QSOs is distributed in the same manner (ii) the physical extent of the reservoir is similar in the two populations. Fig. 3 shows that the far-infrared bright QSOs have similar values of $L'_{\text{CO}(3-2)} \sin^2i/\text{FWHM}^2$ on
average to SMGs. To determine if this means that they have similar gas-mass fractions (potentially indicating they are not more evolved) we need to consider the two simplifying assumptions above.

As their sub-millimetre emission is optically thin it is believed that SMGs do not suffer from an inclination selection bias and so, if we are modelling their gas distributions as disc-like systems (Swinbank et al. 2011), we can adopt a mean inclination of 32.7°, appropriate for randomly orientated discs (Bothwell et al. 2012). Recent studies comparing \(^{12}\)CO linewidths of QSOs and SMGs found no distinction between the populations, indicating that they have the same average inclination (Coppin et al. 2008). As such, in our analysis we adopt the same inclination for QSOs and SMGs. However, optically-identified QSOs such as those studied here may have preferentially biased orientations, as to have identified them as QSOs we must be able to observe their broad-line regions. Even considering situations where the obscuring torus of the AGN is not orientated with the host galaxy, we still expect a bias in the inclination of the gas reservoir. This arises from consideration of when the line of sight to the broad line region is directly through the disk of the host galaxy. If we adopt a mean inclination of 13°, which has been previously suggested (Carilli & Wang 2006), the QSOs sample has an ~ 85% lower gas mass fraction, on average, than the SMGs. The difference is significant at only 2.0σ, but is in the sense expected if QSOs are more evolved systems.

To convert \( L'_{\text{CO}(3-2)} \) to a total gas mass we must make assumptions about the temperature distribution within the gas. \(^{12}\)CO (3-2) has an excitation temperature of 33 K and a critical density of \( 5 \times 10^4 \text{ cm}^{-3} \), meaning it traces warm and/or dense environments. In QSOs it is thought that the gas is close to thermal equilibrium, meaning that the \(^{12}\)CO (3-2) transition traces the majority of the gas in the system (Riechers et al. 2011, Bothwell et al. 2012) show that the \(^{12}\)CO(J, J−1) \( J \geq 2 \) emission lines in SMGs are sub-thermally excited (see also Harris et al. 2010), which is interpreted as an indication for the presence of multiple temperature components: a warm component associated with the star-forming regions and a cooler component associated with extended, quiescent, gas (see also Danielson et al. 2011). Our proxy for the gas mass fraction assumes the conversion from \( L'_{\text{CO}(3-2)} \) to gas mass is the same for both the QSO and SMG populations, which is a conservative assumption. If instead we were to include the differences in line brightness temperature ratio (\( \tau_{31} \)) then the gas mass fraction is roughly doubled in SMGs, the offset between the populations in Fig. 3 becomes larger and the statistical formal significance of the difference increases to 3.6σ (including a bias in the QSO inclination). We conclude that although the estimated gas mass fractions of far-infrared bright QSOs appear similar to typical SMGs, this is subject to a number of assumptions about the kinematics, excitation, sizes and orientations of the two populations.

### 3.3 Gas Consumption Time Scales

A second important measure of the evolutionary state of SMGs and QSOs comes from their gas-consumption timescales: \( M_{\text{gas}}/\text{SFR} \) (or the inverse of this: the star-formation efficiency). In our evolutionary scenario the gas reservoir in SMGs is depleted by star formation as they transform from dusty systems to unobscured QSOs. Our ‘transition’ FIR-bright QSOs are expected to represent a unique evolutionary phase, with prodigious star formation but lower gas masses, and thus shorter gas consumption timescales.

The ratio of the observables, \(^{12}\)CO (3-2) line luminosity, \( L_{\text{CO}(3-2)} \) and far-infrared luminosity, \( L_{\text{FIR}} \), can be used as a proxy for the gas consumption timescale of a galaxy. This ratio has the advantage that we do not hide any differences between populations in the assumptions about the conversion of \(^{12}\)CO (3-2) measurement to \(^{12}\)CO (1-0). We have therefore gathered samples of SMGs and FIR-bright QSOs which have been detected in \(^{12}\)CO (3-2), allowing a direct comparison of observable quantities. We use literature values for the \(^{12}\)CO (3-2) luminosities of QSOs (Coppin et al. 2008, Schumacher et al. 2012), SMGs (Bothwell et al. 2012) and lensed SMGs (Koehn et al. 2008, Iono et al. 2004, Swinbank et al. 2010a, Danielson et al. 2011). We plot our QSOs along with these comparison samples on Fig. 4. We see that of our observations follow a similar trend to the literature QSO values. Combining our re-
sults with the QSOs sample, we find they display $\sim 50 \pm 23\%$ lower ratios of $L_{\text{CO}}(3-2)/L_{\text{FIR}}$ than SMGs, potentially indicating shorter gas consumption timescales. The statistical significance of this difference is only $1.8-\sigma$, but we stress that this interpretation implicitly assumes the same value for $r_{31}$ in the two populations. If we use the proposed $r_{31}$ values for QSOs and SMGs (see Table 2), this would increase the difference between the two populations as the SMG gas masses will roughly double relative to the QSOs (significant at the 3.1-$\sigma$ level), owing to the presence of a reservoir of colder gas in the SMGs, which is not traced by the $^{12}\text{CO}(3-2)$ transition and which is not seen in the QSOs (Riechers et al. 2011).

Thus it appears that the far-infrared bright QSOs not only lack the extended, cool reservoir of gas seen in SMGs (e.g. Ivison et al. 2010, 2011) but also have less warm/dense gas than SMGs, suggesting that they are more evolved.

4 DISCUSSION

In order to study the link between QSOs and SMGs we have selected two far-infrared-detected QSOs at $z \sim 2.5$ (the epoch of peak activity in SMG and QSO populations) whose SMBH masses ($\sim 2 \times 10^8 M_\odot$) are comparable to the average SMBH mass for the SMG population (Alexander et al. 2008). In contrast the majority of previously $^{12}\text{CO}$–detected (unlensed) far-infrared bright QSOs have $M_{\text{BH}} \sim 10^7 - 10^8 M_\odot$ (Coppin et al. 2008), so much larger than the average SMBH mass that they cannot have recently evolved from a typical SMG (as pointed out by Coppin et al. 2008). It is precisely this mismatch in SMBH masses which our study addresses. Given their FIR luminosities and SMBH masses our new sample is a more accurate representation of the typical far-infrared bright QSO population, and hence can be used to test an evolutionary link between SMGs and QSOs, through their gas and dynamical masses, as traced by their $^{12}\text{CO}(3-2)$ emission.

We show in Fig. 4 the distribution of estimated gas and SMBH masses for our two QSOs, as well as the average SMG from Bothwell et al. (2012) and the QSO sample (including limits) from Coppin et al. (2008). To investigate how galaxies might evolve with time we follow Coppin et al. (2008) and overlay a simple evolutionary model based on gas consumption and SMBH growth timescales. We take the average SFR of SMGs from Bothwell et al. (2012) as $500 M_\odot$ yr$^{-1}$ and use this to calculate the reduction in their gas mass with time. In this simple model we assume a constant SFR and do not include mass loss due to winds. By selection our QSOs have SMBH masses similar to the average SMGs, but to estimate the growth of the central SMBH on the gas consumption timescale we follow Eq. 10 from Alexander & Hickox (2012). In line with the measured properties of SMGs, we limit the growth to an Eddington ratio, $\eta = 0.2$ and an efficiency of 0.1 (Alexander et al. 2008), this then predicts the estimated growth in the SMBH mass in parallel to the depletion of the gas reservoir.

In Fig. 5 we plot tracks showing the evolution in the expected gas and SMBH masses for the descendents of SMGs after 50 and 100 Myrs. As can be seen, after 100 Myrs the SMGs in this model are expected to have almost completely depleted their massive, cold gas reservoirs and will have gas masses comparable to those we detect in the far-infrared luminous QSOs. At the same time their SMBHs will have grown by $\sim 50\%$, resulting in masses similar to those seen in our target QSOs. As can be seen from Fig. 4 the rate of growth of the SMBH and the depletion of the gas reservoir can link the properties of a typical SMG to those seen in our far-infrared bright QSOs around $\sim 100$ Myrs later.

Are all SMGs likely to go through a QSO-phase? If these three $z \sim 2-3$ populations (i.e. $S_{60\mu\text{m}} \gtrsim 5$ mJy SMGs and QSOs with SMBH with masses of $\gtrsim 10^8 M_\odot$, which are both far-infrared-bright and -faint) are uniquely related through a simple evolutionary cycle, then the product of their respective space densities and lifetimes should be similar. On average we expect the SMBH lifetimes to be comparable to their gas depletion timescales (Fig. 6) or $\sim 10^8$ yrs (Swinbank et al. 2006; Hickox et al. 2012) and their volume density at $z \sim 2-3$ is $\gtrsim 10^{-5} Mpc^{-3}$ (e.g. Wardlow et al. 2011). In comparison, the QSO volume density at $z \sim 2-3$ (with SMBH masses above $\sim 10^8 M_\odot$) is $\sim 10^{-6} Mpc^{-3}$ (Croom et al. 2009) and estimates of their lifetimes are $\gtrsim 10$ Myrs (Martini & Weinberg 2004; Hosokawa 2002). As noted by a number of previous authors, the space densities and duty cycles of these populations are thus consistent with all SMGs subsequently transforming into a QSO. If they transform through a far-infrared bright QSO phase how long can this be? From Chapman et al. (2003) and Wardlow et al. (2011) we estimate that far-infrared bright QSOs have a volume density at $z \sim 2-3$ of $\sim 10^{-7} Mpc^{-3}$. By comparison to the SMG and QSO lifetimes this implies a duration for this transition phase of just $\sim 1$ Myr. Estimates of lifetimes and space densities for each population are uncertain at $> 2 \times$, and so a qualitative agreement is reasonable. If the QSO influences its host through winds and outflows with characteristic velocities of $\sim 1000 \text{km s}^{-1}$ (e.g. Harrison et al. 2012) then the estimated duration of the far-infrared bright phase would allow these winds to reach kpc-scales, comparable to the likely extent of the gas reservoirs and star-formation activity within these systems (e.g. Tacconi et al. 2008; Ivison et al. 2011). This may help explain the short duration of the ‘transition’ phase, although it may be exhaustion of the gas reservoir by star formation which is allowing these winds to propagate freely.

5 CONCLUSIONS

The main conclusions from our study are:

- We have used IRAM PdBI to search for redshifted $^{12}\text{CO}(3-2)$ emission from two far-infrared bright QSOs at $z \sim 2.5$ selected from the H-ATLAS survey. These QSOs were selected to have SMBH masses of $M_{\text{BH}} \leq 3 \times 10^8 M_\odot$, which are more comparable to typical SMGs than those in samples of high-redshift far-infrared luminous QSOs previously detected in $^{12}\text{CO}$. Our observations detect $^{12}\text{CO}(3-2)$ emission from both QSOs and we derive line luminosities of $L_{\text{CO}(3-2)} = (0.77 \pm 0.15) \times 10^{10} \text{Km s}^{-1} \text{pc}^2$ and $L_{\text{CO}(3-2)} = (1.87 \pm 0.33) \times 10^{10} \text{Km s}^{-1} \text{pc}^2$ for J0908$-0034$ and J0911$+0027$ respectively (Table 2).

\[ \eta = 0.2 \] indicates fast black hole growth. Within uncertainties it is feasible the growth is Eddington limited, $\eta = 1$. 

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• Comparing our FIR-bright QSOs (and similar systems from the literature) with SMGs, we find that the QSOs have similar values of $L_{\text{CO}(3-2)}/L_{\text{FIR}}$, for far-infrared bright QSOs with SMGs, we find that the QSOs have $\sim 50 \pm 23\%$ lower consumption timescales, at a significance of 1.8--$\sigma$. Adopting appropriate line brightness ratios, of $r_{\text{CO}}=1$ for QSO, and $r_{\text{CO}}=0.52$ for SMGs strengthens this conclusion to 3.1--$\sigma$. We conclude that far-infrared bright QSOs have a lower mass of warm/dense gas (probed directly through $^{12}\text{CO}(3-2)$). Combined with previous results [Riechers et al. 2011], showing that QSOs also lack an extended, cool reservoir of gas seen in SMGs, we interpret this as evidence that the far-infrared bright QSOs are at adiabatic evolutionary stage than typical SMGs. In our evolutionary scenario this is consistent with far-infrared bright QSOs being in ‘transition’ from an SMG to a QSO.

• We show that the gas and the SMBH masses in far-infrared bright QSOs and SMGs are consistent with a model where SMGs transform into QSOs on a timescale of $\sim 100$ Myr. Furthermore, the relative volume densities and expected durations of the SMG and QSO phases are consistent with all SMGs passing through a subsequent QSO phase, and we estimate that the likely duration of the far-infrared bright QSO phase is just $\sim 1$ Myr. We note that if necessary this duration is still sufficient to allow the QSO to influence the star formation and gas reservoirs across the full extent of the host galaxy through 1000-km s$^{-1}$ winds and outflows.

The scale of this study is too small to single handedly prove or disprove an evolutionary link between SMGs and QSOs. However the data we have obtained provides further evidence supporting the idea originally proposed by [Sanders et al. 1988] that these populations are linked by an evolutionary sequence. We have compared $^{12}\text{CO}(3-2)$ detected QSOs and SMGs through a number of observable quantities, and find the timescales for gas depletion, and SMBH growth, needed to link SMGs to these sources are consistent.

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