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Testing the Evolutionary Link between SMGs and QSOs: are Submm-Detected QSOs at $z \sim 2$ 'Transition Objects' between These Two Phases?

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Abstract. Local spheroids show a relation between their masses and those of the super-massive black holes (SMBH) at their centres, indicating a link between the major phases of spheroid growth and nuclear accretion. These phases may correspond to high-z submillimetre galaxies (SMGs) and QSOs, separate populations with surprisingly similar redshift distributions which may both be phases in the life cycle of individual galaxies, with SMGs evolving into QSOs. Here we briefly discuss our recent results in Coppin et al. (2008), where we have tested this connection by weighing the black holes and mapping CO in submm-detected QSOs, which may be transition objects between the two phases, and comparing their baryonic, dynamical and Hα-derived SMBH masses to those of SMGs at the same epoch. Our results split our sample of submm-detected QSOs into two categories (although a bigger sample would probably show a continuous trend): (1) CO is detected in 5/6 very optically luminous ($M_{\rm B} \sim -28$) submm-detected QSOs with BH masses $M_{\rm BH} \simeq 10^9$–$10^{10}\,{\rm M}_\odot$, confirming the presence of large gas reservoirs of $M_{\rm gas} \simeq 3.4 \times 10^{10}\,{\rm M}_\odot$. Our BH masses and dynamical mass constraints on the host spheroids suggest, at face value, that these optically luminous QSOs at $z = 2$ lie about an order of magnitude above the local BH-spheroid relation, $M_{\rm BH}/M_{\rm sph}$. However, we find that their BH masses are ~ 30 times too large and their surface density is ~ 300 times too small to be related to typical SMGs in an evolutionary sequence. (2) We measure weaker CO emission in four fainter ($M_{\rm B} \sim -25$) submm-detected QSOs with properties, BH masses ($M_{\rm BH} \simeq 5 \times 10^8\,{\rm M}_\odot$), and surface densities similar to SMGs. These QSOs appear to lie near the local $M_{\rm BH}/M_{\rm sph}$ relation, making them plausible 'transition objects' in the proposed evolutionary sequence linking QSOs to the formation of massive young galaxies and BHs at high-z.

1. Introduction

It appears that every massive, local spheroid hosts a SMBH in its centre whose mass is proportional to that of its host (e.g. Magorrian et al. 1998; Gebhardt et al. 2000). This suggests that the black holes (BHs) and their surrounding galaxies were formed synchronously. This hypothesis has found support from hydrodynamical simulations of galaxy formation, which use feedback from winds and outflows from active galactic nuclei (AGN) to link the growth of the SMBH to that of its host (e.g. Di Matteo, Springel & Hernquist 2005; Hopkins et al. 2005; Bower et al. 2006). Thus these models support a picture, first presented by Sanders et al. (1988), where a starburst-dominated ultra-luminous infrared galaxy (ULIRG), arising from a merger, evolves first into an obscured QSO and then into an unobscured QSO, before finally becoming a passive spheroid.

The high-redshift population of ULIRGs in this proposed evolutionary cycle are the submillimetre (submm) galaxies (SMGs; Smail, Ivison & Blain 1997).

These systems have ULIRG-like bolometric luminosities, $L_{\rm IR} \geq 10^{12}\,{\rm L}_\odot$, and they have many of the properties expected for gas-rich mergers (e.g. Tacconi et al. 2006). This population evolves rapidly out to a peak at $z \sim 2.3$, crudely matching the evolution of QSOs and providing additional circumstantial evidence for a link between SMBH growth and spheroids (Chapman et al. 2005). Two further results have shed light on the evolutionary link between SMGs and QSOs: (1) A modest fraction of optically luminous QSOs at $z \sim 2$ are detected in the submm/mm ($\sim 25\%$; Omont et al. 2003) showing that the QSO- and SMG-phases do not overlap significantly, given the lifetime estimates of the two populations (QSOs make up $\sim 4\%$ of flux-limited samples of SMGs; Chapman et al. 2005). But when a QSO *is* detected in the submm/mm then it is likely to be in the transition phase from an SMG to an unobscured QSO, making its properties a powerful probe of the evolutionary cycle (e.g. Stevens et al. 2005); (2) The evolutionary state of the SMBHs within SMGs can also be judged using the 2-Ms *Chandra* Deep Field North observations to derive accurate AGN luminosities and hence lower limits on the BH masses ($M_{\rm BH}$) in those SMGs with precise redshifts in this region (Alexander et al. 2005a,b; Borys et al. 2005). These studies suggest that the AGN in typical SMGs are growing almost continuously – but that the SMBHs in these galaxies appear to be several times less massive than seen in comparably massive galaxies at $z \sim 0$ (Alexander et al. 2008; see also D.M. Alexander's paper in these conference proceedings). Together these results argue for a fast transition from a star-formation-dominated SMG-phase to the AGN-dominated QSO-phase (Page et al. 2004). Subsequent rapid black hole growth is then required to account for the present-day relation between spheroid and SMBH masses. *Can we confirm this and more generally test the proposed evolutionary link between SMGs and QSOs at the peak of their activity at $z \sim 2$?*

Here we briefly discuss the results of Coppin et al. (2008), who carried out a quantitative test of the proposed link between $z \sim 2$ SMGs and QSOs. We have obtained precise systemic redshifts from UKIRT near-infrared spectroscopy of potential transition QSOs (i.e. submm/mm-detected QSOs) spanning $1.7 < z < 2.6$ and then used the IRAM Plateau de Bure Interferometer (PdBI) to search for CO emission. We relate their dynamical, gas and SMBH masses to SMGs from the PdBI CO survey of Greve et al. (2005) and explore the the proposed evolutionary sequence which links QSOs to the formation of massive young galaxies and SMBHs at high redshift.

2. Comparison of the Submm-Detected QSOs and SMGs

2.1. Gas Content and Star-Formation Efficiencies

We detect CO emission from six of the ten submm-detected QSOs in our sample, confirming that they contain a significant amount of molecular gas and that a large fraction of the mm emission is from starbursts. Adopting a CO-to-gas conversion factor appropriate for local galaxy populations exhibiting similar levels of star formation activity to submm-bright galaxies or QSOs (e.g. ULIRGs; Solomon & Vanden Bout 2005), we derive a median gas mass of the entire sample (i.e. including non-detections) of $(2.5 \pm 0.7) \times 10^{10}\,{\rm M}_\odot$, similar to that found for $z \sim 2$ SMGs and for $z > 4$ QSOs.

The star formation efficiency (SFE) is a measure of how effective a galaxy is at converting its gas into stars and can be represented by the continuum-to-line ratio, or $L_{\rm FIR}/L'_{\rm CO}$, as this ratio presumably traces the star formation rate per total amount of gas in a galaxy. Our submm-detected QSOs have a median of $L_{\rm FIR} = (8.0 \pm 1.9) \times 10^{12}\,{\rm L}_\odot$, and a star-formation rate (SFR) for our sample following Kennicutt (1998) of SFR$=1360 \pm 320\,{\rm M}_\odot\,{\rm yr}^{-1}$. The star formation efficiencies of our QSOs are also comparable to those measured for SMGs, $250 \pm 100\,{\rm L}_\odot\,({\rm K\,km\,s^{-1}\,pc^2})^{-1}$, suggesting that the gross properties of the star formation in the QSOs are like those seen in SMGs. We determine that the submm-detected QSOs have enough cold gas to sustain their current episode of star formation for $\tau_{\rm depletion} \sim {\rm M_{gas}/SFR} \sim 2.5 \times 10^{10}\,{\rm M}_\odot/1360\,{\rm M}_\odot\,{\rm yr}^{-1} \sim 20\,{\rm Myr}$, implying a submm-detected QSO phase lifetime of $2 \times \tau_{\rm depletion} = 40\,{\rm Myr}$.

2.2. Dynamical Masses

CO line widths can be directly converted into dynamical masses, assuming a size and inclination for the gas reservoirs. We note that we find a lower incidence of bimodal CO line profiles in the QSOs, compared to SMGs, which we believe results from a selection bias towards lower average inclination angles for the QSOs. The median CO line width of our sample is $550 \pm 180\,{\rm km\,s^{-1}}$. Adopting a 2 kpc scale size for the gas distribution in the QSOs and a typical inclination of 20° (assuming that the submm-detected QSOs are seen at lower inclination angles, see e.g. Alexander et al. 2008) we derive a median dynamical mass of ${\rm M}(< 2\,{\rm kpc}) \sim (2.1 \pm 1.4) \times 10^{11}\,{\rm M}_\odot$, similar to SMGs (which are assumed to be randomly orientated, i=30°).

2.3. BH Masses and Evolutionary Status

We determine $M_{\rm BH}$ for our QSOs using the Greene & Ho (2005) virial $M_{\rm BH}$ estimator which calculates the BH mass from the observed Hα or Hβ emission line widths and fluxes. We find a median black hole mass in our submm-detected QSO sample of $(1.8 \pm 1.3) \times 10^9\,{\rm M}_\odot$, which is about an order of magnitude larger than SMGs (Alexander et al. 2008). Combined with our dynamical estimates of the spheroid mass above, these yield $M_{\rm BH}/M_{\rm sph} \sim 9 \times 10^{-3}$. This $M_{\rm BH}/M_{\rm sph}$ ratio for this sample of submm-detected QSOs at $z = 2$ is an order of magnitude larger than the local ratio of Häring & Rix (2004), suggesting that BH growth occurs more rapidly than the bulge formation in $z \sim 2$–3 submm-detected QSOs, although $M_{\rm sph}$ suffers from large uncertainties due to the unknown CO radii and inclination angles. This ratio is also significantly above that seen for SMGs at $z \sim 2$ (Alexander et al. 2008; see also D.M. Alexander's paper in these proceedings). However, this comparison masks a broad range in BH masses within our submm-detected QSO sample and so we split the sample into two subsets based on their BH masses.

Looking at the optically luminous submm-detected QSOs in our sample we find that we detect CO emission in 5/6 of them. However, the estimated BH masses for these QSOs, $M_{\rm BH} \simeq 10^9$–$10^{10}\,{\rm M}_\odot$, are too large (and their number densities too small) for them to be related to typical SMGs in a simple evolutionary cycle. We propose that the progenitors of these most massive QSOs are a rare subset of SMGs with $M_{\rm gas} > 4 \times 10^{11}\,{\rm M}_\odot$ with a number density of $\simeq 10\,{\rm deg}^{-2}$ which will be possible to detect with future SCUBA-2 surveys.

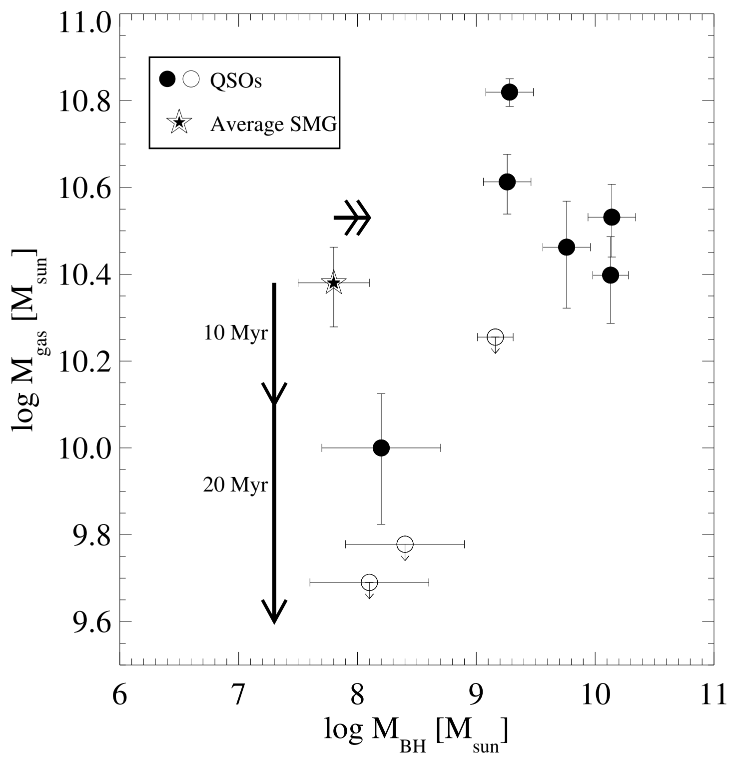

Figure 1. $M_{\rm gas}$ as a function of $M_{\rm BH}$ for our sample of CO-observed submm-detected QSOs. The arrows (offset slightly for clarity) indicate the movement of an average SMG in terms of its gas mass depletion and synchronous BH growth in arbitrary scalable timecales of 10 and 20 Myr, assuming a SFR of $1000\,{\rm M_\odot\,yr^{-1}}$ and Eddington-limited BH growth. This demonstrates that an SMG could evolve into $M_{\rm BH} \simeq 10^8\,{\rm M_\odot}$, $M_{\rm gas} \simeq 0.6\times10^{10}\,{\rm M_\odot}$ submm-detected QSOs in a reasonable timescale, whereas an average SMG would need substantially ($\sim 10\times$) more gas and more time ($>$ SMG lifetime) to evolve into the $M_{\rm BH} \simeq 4\times10^9\,{\rm M_\odot}$, $M_{\rm gas} \simeq 3.0\times10^{10}\,{\rm M_\odot}$ submm-detected QSOs. This suggests that the submm-detected QSOs hosting BHs of $M_{\rm BH} \simeq 10^8\,{\rm M_\odot}$ with $M_{\rm gas} < 1\times10^{10}\,{\rm M_\odot}$ comprise 'transition objects' that we can use to probe the intermediary evolutionary stage between the SMG and luminous QSO phases, while the rarer more luminous QSOs with $M_{\rm BH} > 10^9\,{\rm M_\odot}$ are not related to typical SMGs.

For the optically less luminous ($\sim L^\star$) submm-detected QSOs, we marginally detect one source in CO and obtain sensitive limits for three further QSOs. The BH masses for these systems are $M_{\rm BH} \simeq 10^8\,{\rm M}_\odot$, similar to the estimates for BHs in SMGs. These submm-detected QSOs are consistent with being 'transition' objects between SMGs and submm-undetected QSOs, as it is feasible to link their BH masses to those of SMGs by Eddington limited growth for a period comparable to the gas depletion timescale of the QSOs, $\sim 10\,$Myrs. The space density of these QSOs is also in rough agreement with that expected for the descendents of SMGs given current estimates of the relative lifetimes of QSOs and SMGs. We conclude that these $\sim L^\star$, $M_{\rm BH} > 10^8\,{\rm M}_\odot$ submm-detected QSOs are consistent with being in a very brief prodigious star formation phase, and that they simply do not possess sufficiently large gas reservoirs to sustain the SFR (which is why these might be less often detected in CO), although a larger sample of CO observations of submm-detected QSOs with these BH masses is required for confirmation.

3. Final Remarks

To make further progress on understanding the evolutionary links between SMGs and QSOs requires a larger survey of the submm and CO emission from typical QSOs ($M_{\rm B} \approx -25$), which could be undertaken in the near future with LABOCA and SCUBA-2. In addition, measurements of other CO transitions for the submm-detected QSOs (e.g. from IRAM 30-m, ALMA, EVLA, and SKA) are required to place better constraints on the temperature and density of the molecular gas and thus provide a more accurate determination of the line luminosity ratios and hence total gas masses of these systems. Similarly, higher resolution CO observations are essential to put strong constraints on the reservoir sizes and inclination angles, and hence $M_{\rm dyn}$, needed to compare the two populations. Finally, better measurements of the far-infrared SEDs (with SABOCA, SCUBA-2 or *Herschel*) will yield more accurate measures of $L_{\rm FIR}$ and $T_{\rm dust}$ for submm-detected QSOs to constrain the contribution from an AGN component.

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