Where do $z \approx 2$ Submillimeter-Emitting Galaxies Lie On the Black-Hole–Spheroid Mass Plane?

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Abstract.  Submillimeter-emitting galaxies (SMGs) are $z \approx 2$ bolometrically luminous systems hosting energetic starburst and AGN activity. SMGs may represent a rapid growth phase that every massive galaxy undergoes before lying on the well-established black-hole–spheroid mass relationship in the local Universe. Here we briefly discuss our recent results from Alexander et al. (2008) where we estimated the masses of the black holes in SMGs using the black-hole virial mass estimator, finding $M_{\text{BH}} \approx 6 \times 10^7 M_\odot$ for typical SMGs. We show that the black-hole–spheroid mass ratio for SMGs at $z \approx 2$ was suggestively below that found for massive galaxies in the local Universe and more than an order of magnitude below the black-hole–spheroid mass ratio estimated for $z \approx 2$ quasars and radio galaxies. We demonstrate that SMGs and their progeny cannot lie on the elevated $z \approx 2$ black-hole–spheroid mass relationship of quasars–radio galaxies without overproducing the space density of the most massive black holes ($M_{\text{BH}} \approx 10^9 M_\odot$), unless the galaxy spheroid of SMGs is an order of magnitude lower than that typically assumed ($M_{\text{SPH}} \approx 10^{10} M_\odot$). We also show that the relative black-hole–spheroid growth rates of typical SMGs appear to be insufficient to significantly increase the black-hole–spheroid mass ratio, without requiring long duty cycles ($> 10^9$ years), and argue that a more AGN-dominated phase (e.g., an optically bright quasar) is required to significantly move SMGs (and their progeny) up the black-hole–spheroid mass plane.

1. Introduction

Due to the negative $K$-correction for infrared-luminous galaxies at $z > 1$, submillimeter/millimeter surveys select the most bolometrically luminous systems in the Universe (e.g., Blain et al. 2002). After intense multi-wavelength follow-up observations it is now clear that submillimeter-emitting galaxies (SMGs; $f_{850\mu m} > 4$ mJy) are gas-rich massive galaxies at $z \approx 2–4$ hosting energetic starburst and AGN activity (e.g., Smail et al. 2002; Alexander et al. 2005a; Chapman et al. 2005); the stellar–dynamical and CO gas masses of these galaxies are typically $\approx 10^{11} M_\odot$ and $\approx 3 \times 10^{10} M_\odot$, respectively (e.g., Swinbank et al. 2004; Borys et al. 2005; Greve et al. 2005). The compactness and high inferred gas density of the CO emission from SMGs suggests that the CO dynamics trace the mass of the galaxy spheroid (e.g., Bouche et al. 2007). It is commonly believed that SMGs represent a major-merger induced growth phase that causes rapid black-hole–spheroid growth, and it is possible that every massive galaxy ($> 1–3 L_\ast$) in the local Universe underwent at least one submillimeter-bright phase at some time in the distant past (e.g., Swinbank et al. 2006).

The close relationship between supermassive black-hole (SMBH) and spheroid mass–luminosity–velocity dispersion in the local Universe (e.g., Gebhardt et al.
(2000; Haring & Rix 2004) suggests that the growth of SMBHs and galaxy spheroids was concordant. The potentially rapid growth rates of the SMBH and host galaxy in SMGs could cause these systems to deviate significantly from the locally defined black-hole–spheroid mass relationship, if the growth of one component is much faster than the other component. It is therefore of interest to constrain the SMBH masses and relative black-hole–host galaxy growth in SMGs to give insight into the formation and evolution of today’s massive galaxies.

Using X-ray luminosity derived black-hole masses and photometrically determined stellar masses, Borys et al. (2005) showed that SMGs lie more than an order of magnitude below the locally defined black-hole–spheroid mass relationship, under the assumption of Eddington-limited SMBH accretion. While Borys et al. (2005) provided useful first-order constraints, it is necessary to determine the SMBH masses of SMGs without having to assume the Eddington ratio of the SMBH. Here we present recent results from Alexander et al. (2008), where we used the virial SMBH mass estimator to calculate SMBH masses for a handful of SMGs with detected broad emission lines. These results are used to constrain the relative black-hole–spheroid mass ratio of SMGs and to explore how quickly the SMBH and host galaxy is growing in these systems.

2. Weighing the Black Holes in SMGs

Black-hole masses ($M_{\text{BH}}$) have been directly measured for a small number of galaxies in the local Universe, on the basis of the velocity dispersion of stars/gas in the vicinity of the SMBH (e.g., Gebhardt et al. 2000). Black holes cannot be “weighed” in the same way at high redshift due to poorer spatial resolution and lower signal-to-noise ratio data. However, the well-established virial SMBH mass estimator, which works on the assumption that the broad-line regions (BLRs) in AGNs are virialized, provides an apparently reliable, if indirect, measurement of SMBH masses in high-$z$ AGNs (e.g., Kaspi 2000).

The virial SMBH mass estimator is somewhat restrictive for SMGs since the majority of the sources are heavily obscured (e.g., Alexander et al. 2005b; Chapman et al. 2005). However, the identification of broad Hα/Hβ emission from a small number of SMGs (Swinbank et al. 2004; Takata et al. 2006) provides the opportunity to estimate SMBH masses for a handful of sources so far. In Alexander et al. (2008) we used the virial estimator of Greene & Ho (2005), which calculates $M_{\text{BH}}$ solely on the properties of the Hα/Hβ emission line and reduces potential uncertainties on the luminosity of the AGN (e.g., contaminating emission from the host galaxy or an accretion-related jet) when compared to other estimators. Taking the six SMGs from Swinbank et al. (2004) and Takata et al. (2006) with broad emission lines (FWHM $> 1000$ km s$^{-1}$) that appear to be intrinsic to the central source (i.e., unrelated to AGN outflows), we find relatively modest SMBH masses [average $M_{\text{BH}} \approx (1 - 3) \times 10^8 M_\odot$, depending upon the assumed geometry of the broad-line region; see §3.2 in Alexander et al. 2008]. Broad-line SMGs typically have relatively narrow emission lines when compared to the optically bright quasar population ($\approx 2500$ km s$^{-1}$ vs typically $\approx 5000$ km s$^{-1}$), which is a major factor that leads to the comparatively low SMBH masses. Under the assumption that X-ray obscured SMGs have essentially the same AGN properties as the broad-line SMGs
but are obscured due to the presence of an optically and geometrically thick torus aligned along the line of sight (i.e., the Unified AGN model), we can calculate the Eddington ratio (defined as $L_{\text{AGN}}/L_{\text{Edd}}$; i.e., $\eta$) of the broad-line SMGs and derive SMBH masses for the X-ray obscured SMGs utilising the Eddington-limited SMBH mass constraints in Alexander et al. (2005a). We find a typical Eddington ratio for the broad-line SMGs of $\eta \approx 0.2$, leading to $M_{\text{BH}} \approx 6 \times 10^7 M_\odot$ for a typical X-ray obscured SMG; see §3.4 in Alexander et al. (2008) for further justification.

Due to a number of poorly constrained assumptions that need to be made to calculate Eddington ratios (i.e., the conversion from X-ray luminosity to mass accretion rate, the derivation of SMBH masses, and the calculation of the Eddington luminosity limit), the uncertainties on any estimation of an Eddington ratio are large, particularly at high redshift. However, the primary reason for the derivation of the Eddington ratios in Alexander et al. (2008) was to provide a way to estimated SMBHs for the X-ray obscured SMGs, by scaling the X-ray luminosities of the broad-line SMGs to those of the X-ray obscured SMGs. In this approach, we only make the assumption that the broad-line SMGs are the unobscured counterparts of the larger X-ray obscured SMG population, and therefore all of the above uncertainties become negligible.

Two alternative scenarios for the relationship between broad-line SMGs and X-ray obscured SMGs are that the broad-line SMGs either represent a later stage in the evolution of the SMG population or are a higher SMBH accretion rate phase (e.g., Alexander et al. 2005b; Stevens et al. 2005; Coppin et al. 2008). Under these assumptions, the SMBH masses of the X-ray obscured SMGs could be higher than those derived here (i.e., up to the $M_{\text{BH}} \approx 3 \times 10^8 M_\odot$ maximum calculated for the broad-line SMGs). However, as we show in §4, it is unlikely that the SMBHs hosted by typical SMGs can be this massive. In any case, given the similarity between the estimated Eddington ratios of the broad-line SMGs and a handful of obscured ultra-luminous infrared galaxies (ULIRGs) in the local Universe (the SMBH masses for the obscured ULIRGs were calculated using the broad Pa$\alpha$ emission line, which is detected in a small fraction of obscured systems; e.g., Veilleux, Sanders, & Kim 1999; see §4.1 in Alexander et al. 2008), we favour $\eta \approx 0.2$ and $M_{\text{BH}} \approx 6 \times 10^7 M_\odot$ for a typical X-ray obscured SMG. See §4 of Alexander et al. (2008) for evidence that the AGNs found in $z \approx 2$ SMGs are scaled-up versions of those found in local ULIRGs.

3. Exploring the Black-Hole–Spheroid Mass Relationship in SMGs

By combining the SMBH mass constraints with host-galaxy masses, in Alexander et al. (2008) we explored the $M_{\text{BH}}-M_{\text{SPH}}$ relationship for $z \approx 2$ SMGs. On the basis of CO spectroscopy and interferometric imaging, the dynamical masses of SMGs within the central 2–4 kpc are $M_{\text{DYN}} \approx 10^{11} M_\odot$ (e.g., Greve et al. 2003; Bouche et al. 2007); similar constraints are derived from H$\alpha$ emission-line widths (Swinbank et al. 2004). Given the high inferred gas density of the CO emission in SMGs (comparable to or higher than the mass density of galaxy spheroids in the local Universe) it is likely that this dynamical estimate corresponds to the mass of the spheroid (e.g., Bouche et al. 2007). By comparison, the average stellar mass derived from ultra-violet–near-IR photometric data by
Figure 1. Black-hole–host galaxy (corresponding to the spheroid mass for these systems) mass relationship for SMGs and other systems (as indicated). SMGs (circles) cannot lie a factor \( \approx 4–6 \) above the local relationship (as found for \( z \approx 2 \) quasars and radio galaxies; Peng et al. 2006; McLure et al. 2006) without overproducing the local black-hole mass density; see §4 for discussion. The solid square indicate where X-ray luminous broad-line SMGs would lie, assuming that the average CO dynamical mass represents the spheroid mass in these systems, and shows that this subset of the broad-line SMG population could be more evolved than typical systems. The solid bar indicates how the SMBH masses for the SMGs varies depending upon the assumed Eddington ratio (\( \eta \)). This figure is taken from Alexander et al. (2008); see §5 of that paper for further details.

Borys et al. (2005) is \( 2 \times 10^{11} M_\odot \); here we only consider the six \( z > 1.8 \) SMGs in Borys et al. (2005) that do not have UV or near-IR excess emission over that expected from stars, giving a value \( \approx 2 \) times lower than estimated by Borys et al. (2005). The stellar-mass estimate is slightly higher than the masses estimated from CO and Hα dynamics, and may be more representative of the overall mass
of the system rather than just the spheroid; however, we note that uncertainties in photometrically derived stellar masses are typically a factor of $\approx 3$.

In Fig. 1 we show the average SMBH–host-galaxy mass ratio for the X-ray obscured SMGs and compare it to that determined for distant quasars–radio galaxies (e.g., McLure et al. 2006; Peng et al. 2006) and local obscured ULIRGs with broad Pa$\alpha$ derived SMBH masses. The SMBHs of the X-ray obscured SMGs are suggestively smaller than those of comparably massive galaxies in the local Universe, by a factor of $\approx 3–7$, although given the number of assumptions in the determination of these quantities this result should not be considered statistically conclusive. However, we note that we find the same result for local ULIRGs, providing corroborating evidence that SMBHs in $z \approx 2$ SMGs are smaller than those found for comparably massive galaxies in the local Universe.

Importantly, our results are statistically inconsistent with those derived for $z \approx 2$ radio galaxies and quasars, which suggested that distant galaxies have SMBHs a factor of $\approx 4–6$ times more massive than those found for comparably massive galaxies in the local Universe (more than an order of magnitude higher than found here for SMGs; e.g., McLure et al. 2006; Peng et al. 2006); see Fig. 1. One factor in this discrepancy may be related to the selection of the source populations since high-$z$ radio galaxies and quasars by definition have massive SMBHs and are likely to be comparatively evolved objects (e.g., Lauer et al. 2007); indeed, the X-ray luminous subset of the broad-line SMGs would lie close to or above the local SMBH–host galaxy relationship if it was assumed that they are hosted by galaxy spheroids as massive as the typical SMG population (see Fig. 1). However, as shown in Alexander et al. (2008), there is a key factor why typical SMGs do not lie on the $M_{\text{BH}}$–$M_{\text{SPH}}$ relationship found for $z \approx 2$ quasars and radio galaxies: they would overproduce the mass density of the most massive SMBHs in the local Universe.

4. Why SMGs cannot lie on the Elevated Black-Hole–Spheroid Mass Relationship Found for $z \approx 2$ Quasars and Radio Galaxies

If we assume that SMGs lie a factor $\approx 4–6$ above the local $M_{\text{BH}}$–$M_{\text{SPH}}$ relationship, as found for $z \approx 2$ quasars and radio galaxies then, given a spheroid mass of $10^{11} M_\odot$, they would have to host black holes of $M_{\text{BH}} \approx 10^9 M_\odot$. The space density of $M_{\text{BH}} = 10^9 M_\odot$ SMBHs in the local Universe is $\Phi \approx 10^{-5}$ Mpc$^{-3}$, which is the same as the observed space density of SMGs at $z \approx 2$. This scenario is therefore only plausible if SMGs are continuously bright at submm wavelengths and never “switch off” over the peak $z = 1.7–2.8$ redshift range of submm activity (i.e., a duty cycle of $\approx 1.5$ Gyrs). In order to stay bright at submm wavelengths and maintain such high star-formation rates for such a long duration, gas masses an order of magnitude larger than those found for SMGs would be required, which would only be feasible if the gas reservoir of SMGs is continuously replenished. Furthermore, the ultimate stellar masses of SMGs after a 1.5 Gyr lifecycle of star formation and SMBH growth would be $> 10^{12} M_\odot$, which would lead to even larger SMBH masses, further compounding the SMBH space-density problem. Indeed, given the measured gas masses of SMGs, the submm-bright lifetime of SMGs is more likely to be $\approx 100–300$ Myrs (i.e., at any given snapshot only $\approx 10\%$ of galaxies that will be SMGs over the peak
$z = 1.7\text{--}2.8$ redshift range will be bright at submm wavelengths), which leads to a duty-cycle corrected space density for SMGs that is an order of magnitude larger than that found for SMBHs with $M_{\text{BH}} = 10^9 M_\odot$ in the local Universe ($\Phi \approx 10^{-4} \text{ Mpc}^{-3}$).

The SMBH space-density arguments alone show that typical SMGs cannot host black holes with $M_{\text{BH}} \approx 10^9 M_\odot$. However, we can consider an alternative scenario, where the spheroid masses of SMGs are overestimated by an order of magnitude (i.e., $M_{\text{SPH}} \approx 10^{10} M_\odot$), which would place SMGs a factor of $\approx 4\text{--}6$ above the local relationship. This hypothetical scenario appears unlikely since the large star-formation rates of SMGs and the likely duration of submm-bright activity would lead to an increase in stellar mass of $\approx 10^{11} M_\odot$. Therefore, unless this additional stellar growth only occurs outside of the spheroid region, the mass of the spheroid in a typical SMG is likely to be $\gg 10^{10} M_\odot$ (i.e., given the high star-formation rates of SMGs it would take just $\approx 10^7$ yrs to "build" a stellar mass of $10^{10} M_\odot$). Since the observed spatial extent of the CO emission in SMGs is confined to a compact region with an inferred gas density consistent with that expected to produce a galaxy spheroid (e.g., Bouche et al. 2007), this suggests that the star formation is predominantly confined to the galaxy spheroid region, making this scenario unlikely.

We can also determine the largest SMBH mass that SMGs could host and then explore whether the inferred spheroid mass is plausible, under the assumption that the $M_{\text{BH}}$--$M_{\text{SPH}}$ ratio at $z \approx 2$ is a factor $\approx 4\text{--}6$ above the local relationship. On the basis of the duty-cycle corrected space density of SMGs ($\Phi \approx 10^{-4} \text{ Mpc}^{-3}$), the largest possible SMBHs that typical SMGs could host without overproducing the local SMBH space density are $M_{\text{BH}} \approx 3 \times 10^8 M_\odot$, which would imply that the spheroid in SMGs could not be larger than $M_{\text{SPH}} \approx (3\text{--}5) \times 10^{10} M_\odot$. Since we have considered the largest possible SMBH mass for SMGs, we are clearly taking the extreme assumption that no significant SMBH growth will occur in SMGs between $z \approx 2$ and the present day. Furthermore, this spheroid mass constraint is consistent with the average gas mass of SMGs and would therefore dictate that the spheroid can only significantly grow during the SMG phase. These scenarios place severe constraints on how much SMGs and their progeny can evolve and therefore appear unlikely. Although here we have considered the largest SMBH that an SMG can host, we note that significantly smaller SMBHs would lead to spheroid masses of order $\approx 10^{10} M_\odot$ (assuming that the $M_{\text{BH}}$--$M_{\text{SPH}}$ ratio is a factor $\approx 4\text{--}6$ above the local relationship), which appears unlikely unless the star formation in SMGs is predominantly occurring outside of the spheroid region; see constraints above. We note that Hopkins et al. (2006) took a similar approach to estimate the general degree of evolution in the $M_{\text{BH}}$--$M_{\text{SPH}}$ ratio, given space-density constraints in the local Universe, also finding that typical $z \approx 2$ systems cannot lie far from the local relationship.

5. How far can SMGs move up the Black-Hole–Spheroid Mass Plane?

Due to the large space density of SMGs and their rapid growth rates, our constraints show that SMGs and their progeny cannot lie the factor $\approx 4\text{--}6$ above the local relationship found for $z \approx 2$ quasars and radio galaxies. However,
Figure 2. Growth times (i.e., the time it would take to double the current mass) of the SMBH and host galaxy (spheroid) for SMGs (solid circle) and the X-ray luminous subset of the broad-line SMG population (solid square). Although very uncertain, the SMBH–host galaxy growth of SMGs is consistent with no net change in their $M_{\text{BH}} - M_{\text{GAL}}$ ratios for likely submm-bright lifetimes and a more AGN-dominated growth phase would be required to significantly move SMGs and their progeny up the $M_{\text{BH}} - M_{\text{GAL}}$ plane. The X-ray luminous subset of the broad-line SMG population may represent this AGN-dominated phase; see also Fig. 3 and §5.2 of Alexander et al. (2008) and Coppin et al. (2008).

Our constraints do not rule out the possibility that the SMBHs and spheroids in SMGs will grow beyond our currently derived $M_{\text{BH}} - M_{\text{SPH}}$ ratio, although they do provide tight limits. As shown above, on the basis of the space-density constraints of SMGs at $z \approx 2$, the ultimate SMBH mass of typical SMGs cannot exceed $M_{\text{BH}} \approx 3 \times 10^8 \, M_\odot$, limiting the amount of SMBH growth in SMGs and their progeny by up-to a factor of $\approx 6$.

We can explore how quickly SMGs can move up the $M_{\text{BH}} - M_{\text{SPH}}$ plane by estimating the growth rates of the SMBH and host galaxy; see Fig. 2. Although
highly uncertain due to a number of assumptions required to determine key parameters, the relative growth of the SMBH and host galaxy appear to be similar, indicating that SMGs will not significantly move up the $M_{\text{BH}}-M_{\text{SPH}}$ plane over the likely duration of the submm-bright phase. For example, it would take $\approx 400$ Myrs for the SMBH to grow by the maximum factor of $\approx 6$ allowed. These analyses suggest that an AGN-dominated growth phase, where the SMBH grows substantially faster than the host galaxy, is required to significantly move SMGs and their progeny up the SMBH–spheroid mass plane. An AGN-dominated growth phase may be associated with optically bright quasars, where the relative SMBH growth could exceed that of the galaxy spheroid. Indeed, the relative SMBH–host galaxy growth times of the X-ray luminous subset of the broad-line SMGs is sufficient to increase the SMBH–spheroid mass ratio by a factor of $\approx 8$ over 200 Myrs; see Fig. 2 and §5.2 of Alexander et al. (2008). We note that the CO-derived gas and host-galaxy masses of submm-detected optically luminous quasars are consistent with those expected for an AGN-dominated phase that follows the rapid SMBH–spheroid growth phase of luminous SMGs Coppin et al. (2008), providing evidence for this evolutionary scenario.

We finally note that given the rapid growth rates of SMGs (i.e., star-formation rates high enough to build a massive spheroid of $M_{\text{SPH}} \approx 10^{11} M_\odot$ in 100 Myrs), it is quite amazing that the $M_{\text{BH}}-M_{\text{SPH}}$ ratio does not deviate far from that seen in massive galaxies in the local Universe. This suggests that some mechanism connects and regulates the growth of both components.

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