Weighing Black Holes in High-Redshift SCUBA Galaxies

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Abstract.
Deep SCUBA surveys have uncovered a population of dust-enshrouded star-forming galaxies at \( z \approx 2 \). Using the ultra-deep 2 Ms Chandra Deep Field-North survey we recently showed that a large fraction of these systems are also undergoing intense black-hole growth. Here we provide further constraints on the properties of the black holes in SCUBA galaxies using the virial black-hole mass estimator. We show that typical SCUBA galaxies are likely to host black holes with \( M_{\text{BH}} \approx 10^7 – 10^8 \, M_\odot \) which are accreting at, or close to, the Eddington limit. These results provide qualitative support for our earlier conclusion that the growth of the black hole lags that of the host galaxy in these massive ultraluminous galaxies.

1. Tracing the Growth of Massive Galaxies

Deep surveys over the past decade have revolutionised our understanding of the high-\( z \) Universe and mapped the history of star formation out to \( z \approx 6 \) (e.g., Madau, Pozzetti, & Dickinson 1998). Over the same timescale, the finding that every massive galaxy hosts a central super-massive black hole (SMBH) with a mass proportional to that of its spheroid (e.g., Tremaine et al. 2002) has raised the surprising possibility that the growth of galaxies and their SMBHs are concurrent, despite nine orders of magnitude difference in size scale.

The most active sites of star formation at high redshift are identified with (sub-)millimetre emitting galaxies (SMGs), such as those detected in deep SCUBA surveys (e.g., Smail et al. 2002). The estimated star-formation rates of these systems are large enough to form a massive galaxy of \( \approx 10^{11} \, M_\odot \) in just \( 10^8 \) yrs (e.g., Chapman et al. 2005; Greve et al. 2005). After intense multi-wavelength follow-up observations it is clear that these SMGs are already massive at their average redshift of \( z \approx 2 \) and are sufficiently gas rich to maintain a vigorous level of star formation for a further \( \approx 5 \times 10^7 \) yrs (e.g., Swinbank et al. 2004; Tecza et al. 2004; Tacconi et al. 2006). These results suggest that SMGs pinpoint the formation of local \( > M_\ast \) early-type galaxies. Given the apparent connection between the growth of galaxies and their black holes, what can be understood about the growth of black holes in SMGs?

2. The Growth of Black Holes in SMGs

Using ultra-deep Chandra observations (the 2 Ms Chandra Deep Field-North survey) we recently showed that \( \approx 40\% \) (perhaps all) of the bright \( (f_{850\mu m} > 4 \, \text{mJy}) \) SMG population host heavily obscured Active Galactic Nuclei (AGN)
activity (e.g., Alexander et al. 2005a; Alexander et al. 2005b). The energetics of
the AGN activity was found to be (typically) too low to explain the huge
bolometric output of these objects, which is almost certainly dominated by star
formation (see also, e.g., Chapman et al. 2004; Ivison et al. 2004). However,
the large AGN fraction implies that the SMBHs are growing almost continuously
throughout these periods of vigorous star formation (i.e., > 40% duty cycle of
SMBH fueling). This almost continuous SMBH growth suggests that there is
an abundance of available fuel, hinting that the accretion may be occurring at,
or close to, the Eddington limit. Although hypothetical, this picture is in good
agreement with direct predictions for the growth of SMBHs in SMG-like systems
(e.g., Di Matteo, Springel, & Hernquist 2005; King 2005; Granato et al. 2006).
Under the assumption of Eddington-limited accretion we showed that the masses
of the SMBHs in typical SMGs are \(< \, 10^8 \, M_\odot\) (Alexander et al. 2005a). Fig. 1
shows the mass accretion rate for SMGs hosting AGN activity and a comparison
sample of \(M_B < -24\) quasars.

Utilising deep rest-frame optical–near-IR observations we also directly es-
timated the stellar masses of these X-ray detected SMGs, finding that their
Eddington-limited SMBH masses are \(\approx 1–2\) orders of magnitude below that mea-
sured for comparably massive galaxies in the local Universe (Borys et al. 2005).
This result suggests that either (1) the growth of the SMBH lags that of the
host galaxy in SMGs, or (2) the SMBHs in SMGs are accreting at sub-Eddington
rates. The former is in stark contrast with the growth of SMBHs estimated for
high-z quasars and radio galaxies (e.g., Walter et al. 2004; McLure et al. 2006)
while the latter is in conflict with that predicted by models for the growth of
SMG-like systems with an abundance of available fuel. The aim of this brief
contribution is to further constrain the properties of the black holes in SMGs.

3. The Properties of the Black Holes in SMGs

Black-hole masses (\(M_{BH}\)) for a small number of galaxies in the local Universe
have been directly measured 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
black-hole mass estimator, which works on the assumption that the broad-line
regions (BLRs) in AGN are virialized, provides an apparently reliable, if indi-
rect, measurement of SMBH masses in high-z AGN (e.g., Kaspi 2000). Using this
technique, the masses of SMBHs in quasars up to \(z \approx 6.4\) have been estimated
(e.g., Willott et al. 2003; McLure & Dunlop 2004).

The virial black-hole mass estimator is somewhat restrictive for SMGs since
the majority of the sources are heavily obscured (e.g., Alexander et al. 2005b).
However, the identification of broad H\(\alpha\) emission from a small number of SMGs
(Swinbank et al. 2004) provides the opportunity to estimate SMBH masses for
a handful of sources so far. Here we use the virial estimator of Greene & Ho
(2005), which calculates \(M_{BH}\) solely on the properties of the H\(\alpha\) emission line
and reduces potential uncertainties on the luminosity of the AGN (e.g., contami-
nating emission from the host galaxy or an accretion-related jet) when compared
to other estimators.
Figure 1. Black-hole mass accretion rate vs redshift for the SMGs (circles) and a comparison sample of $M_B < -24$ quasars (blue dots). The SMGs are split into typical SMGs with ultra-deep X-ray constraints from Alexander et al. (2005a) (solid circles) and an X-ray detected SMG with broad Hα from Swinbank et al. (2004) (open circle); the mass accretion rates for the SMGs are determined following the luminosity dependent bolometric correction factors of Marconi et al. (2004) and are consistent with Alexander et al. (2005a). The quasar data is from McLure & Dunlop (2004). The dotted line indicates the approximate Eddington-limited mass accretion rate for a $10^8 M_\odot$ black hole ($M_{BH}(\text{Edd})$) while the solid and dashed curves show the median and interquartile ranges for the quasars, respectively. Typical SMGs have mass accretion rates approximately an order of magnitude below those of coeval quasars, indicating smaller black-hole masses for comparable Eddington accretion rates ($M_{BH} < 10^8 M_\odot$). Adapted from Alexander et al. (2005a).

Fig. 2 shows the broad Hα properties of the four SMGs from Swinbank et al. (2004) with FWHM(Hα) > 1000 km s$^{-1}$. These SMGs have narrow Hα emission lines when compared to the quasar population ($\approx 2000$ km s$^{-1}$ vs typically
≈ 5000 km s⁻¹) which leads to relatively modest SMBH masses (average $M_{BH} \approx 5 \times 10^7 M_\odot$). Can these SMBH masses also be considered typical of the overall SMG population? Although we cannot directly measure the broad Hα emission-line properties of the other SMGs in our sample, we can predict their broad Hα luminosity using the X-ray luminosities from Alexander et al. (2005b) and the X-ray–Hα luminosity relationship found by Imanishi & Terashima (2004) for low-z galaxies with luminosities comparable to those of the SMGs (see also Ward et al. 1988). The predicted broad Hα luminosity for typical SMGs is up-to $\approx 3 \times 10^{44}$ erg s⁻¹, consistent with the maximum luminosity of the X-
Figure 3. Mass accretion rate vs black-hole mass of the two X-ray detected SMGs with broad Hα (circles) and a comparison sample of $M_B < -24$ quasars (blue dots); see Figs. 1 & 2 for further definitions. The dotted and dashed lines indicate the relationship for Eddington-limited accretion and accretion at 10% of the Eddington limit, respectively. The SMGs have properties consistent with efficient black-hole accretion (i.e., at, or close to, the Eddington limit).

ray detected SMGs with broad Hα emission. Therefore, under the reasonable assumption that the broad Hα emission line has the same intrinsic width in all SMGs but is undetected in most systems due to the presence of dust/gas along the line of site to the BLR (i.e., the unified model of AGN; Antonucci 1993), the predicted SMBH mass range for typical SMGs is $M_{BH} \approx 10^7-10^8 \ M_\odot$; see Fig. 2. Indeed, the masses of the SMBHs in typical SMGs seem unlikely to be much larger than $\approx 10^8 \ M_\odot$ unless the majority of SMGs represent a population distinct from those with detected broad Hα and have intrinsically broader Hα emission, an assumption that would fly in the face of current wisdom (e.g., Page et al. 2004; Stevens et al. 2005).
What does this result imply for the relative growth of the SMBH and host galaxy in SMGs? Clearly robust masses are required to provide a quantitative answer to this question. However, given the SMBH–spheroid mass ratio in the local Universe ($\approx 1.3 \times 10^{-3}$; e.g., [Merritt & Ferrarese 2001]), so long as SMGs have stellar masses $> 10^{10}–10^{11} \, M_\odot$ then the growth of their SMBHs are likely to lag that of the host galaxy. Current photometric and dynamical mass estimates suggest that the host galaxies of SMGs are of order $\approx 10^{11} \, M_\odot$ (e.g., [Swinbank et al. 2004; Borys et al. 2005; Tacconi et al. 2006]).

Fig. 3 shows the mass accretion rate vs the virial black-hole mass for the two X-ray detected SMGs with broad Hα. This plot provides a measure of how efficiently the SMBHs are growing in SMGs. Even taking into account the large uncertainties, the SMGs appear to be accreting at $> 10\%$ the Eddington limit and the average mass accretion rate is comparable to the Eddington limit; the finding that AGNs with similarly narrow BLRs (such as narrow-line Seyfert 1s; e.g., [Osterbrock & Pogge 1985]) are accreting at comparable rates provides tangential support for this result (e.g., [McLure & Dunlop 2004]). Evidently quantitative conclusions cannot be drawn from such a small and heterogeneous sample, however, these results provide qualitative support for the models that predict that SMGs are undergoing a rapid Eddington-limited SMBH growth phase.

4. Conclusions and Discussion

We have shown that the black holes in high-$z$ SMGs appear to be undergoing almost continuous growth throughout periods of intense star formation. Using the black-hole virial mass estimator we predict that typical SMGs are likely to host $M_{\text{BH}} \approx 10^7–10^8 \, M_\odot$ black holes which are accreting at, or close to, the Eddington limit. These results provide qualitative support for (1) the models that predict that SMGs are undergoing a rapid Eddington-limited SMBH growth phase, and (2) our earlier conclusion that the growth of the SMBH lags that of the host galaxy in these massive ultraluminous galaxies.

More detailed analyses of a larger sample of SMGs with high signal-to-noise near-IR spectroscopy and/or spectropolarimetry in addition to robust host-galaxy mass estimates will provide a more quantitative test of these conclusions. Over the next few years, the expected 10–100 pc resolution of ALMA will also allow the detailed dynamics of the gas within the environment of the feeding SMBH to be probed, providing the potential to directly track the influence of the SMBH on the dynamics of the gas.

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