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Rapid Growth of Black Holes in Massive Star-Forming Galaxies

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The tight relationship between the masses of black holes and galaxy spheroids in nearby galaxies[1] implies a causal connection between the growth of these two components. Optically luminous quasars host the most prodigious accreting black holes in the Universe and can account for $\gtrsim 30$ % of the total cosmological black-hole growth[2,3]. As typical quasars are not, however, undergoing intense star formation and already host massive black holes ($> 10^8\ M_\odot$)[4,5], there must have been an earlier pre-quasar phase when these black holes grew (mass range $\approx 10^6$–$10^8\ M_\odot$). The likely signature of this earlier stage is simultaneous black-hole growth and star formation in distant (i.e., $z > 1$; > 8 billion light years away) luminous galaxies. Here we report ultra-deep X-ray observations of distant star-forming galaxies that are bright at submillimetre wavelengths. We find that the black holes in these galaxies are growing almost continuously throughout periods of intense star formation. This activity appears to be more tightly associated with these galaxies than any other coeval galaxy populations. We show that the black-hole growth from these galaxies is consistent with that expected for the pre-quasar phase.

The most intense sites of star formation at high redshift are associated with submillimetre galaxies (SMGs)[6–9]. SMGs are amongst the most bolometrically luminous galaxies in the Universe ($L_{\rm BOL} \approx 10^{13}\ L_\odot$) and the majority of the population is coeval with the peak in quasar activity (i.e., $z \approx 1.5$–3.0)[7,9]. The apparent association of SMGs with some quasars and the similarity in the comoving space densities of SMGs and optically luminous ($M_{\rm B} < -24$) quasars (when corrected for probable source lifetimes) provides direct evidence for an evolutionary connection between SMGs and quasars[5,10,11]. However, in contrast to quasars, the bolometric output of SMGs appears to be dominated by powerful star-formation activity and any black-hole accretion [i.e., Active Galactic Nuclei (AGN) activity] is comparatively weak[12,13]. Given the large available molecular gas supply (typically $\approx 3 \times 10^{10}\ M_\odot$)[14], SMGs can fuel this luminous star-formation activity for $\approx 10^8$ yrs (ref 14,15). Various pieces of complementary observational support have also shown that SMGs are massive galaxies (typically $\approx 10^{11}\ M_\odot$), suggesting that they will become $\gtrsim M_*$ spheroid-dominated galaxies in the local Universe[14,16,17].

AGN activity has been identified in many SMGs[6,12]. However, the difficulty in obtaining high-quality optical spectra and reliable source redshifts has hindered a complete census of AGN activity in SMGs. We have initiated a project investigating the properties of AGNs in SMGs using deep optical spectroscopic data (obtained with the 10-m Keck telescope)[9] and ultra-deep X-ray observations (the 2 Ms Chandra Deep Field-North; CDF-N)[18]. As X-ray emission appears to be an ubiquitous property of AGNs that is comparatively impervious to obscuration, the combination of these deep datasets provides a detailed census of AGN activity in SMGs. Here we focus on the role of black-hole accretion in SMGs and the growth of black holes in massive galaxies. The assumed cosmology is $H_0 = 65$ km s^{-1} Mpc^{-1}, $\Omega_{\rm M} = 1/3$, and $\Omega_\Lambda = 2/3$.

The parent SMG sample comprises 20 submillimetre detected (with the SCUBA camera on the James Clerk Maxwell Telescope) sources in the CDF-N region whose positions have been reliably located from their radio emission and which could then be spectroscopically targeted[9]. These sources have overall properties consistent with the general SMG population ($S_{850\mu{\rm m}} \approx 4$–$12$ mJy and $z = 0.56$–2.91, with the majority at $z > 2$)[6–9]. Seventeen ($\approx 85\%$) of the 20 SMGs are detected at X-ray energies. A detailed investigation of the nature of the X-ray emission has revealed AGN activity in at least 15 ($\approx 75\%$) SMGs[19]; the properties of these sources are given in Table 1. The X-ray properties of the other 5 ($\approx 25\%$) SMGs are consistent with those expected from luminous star-formation

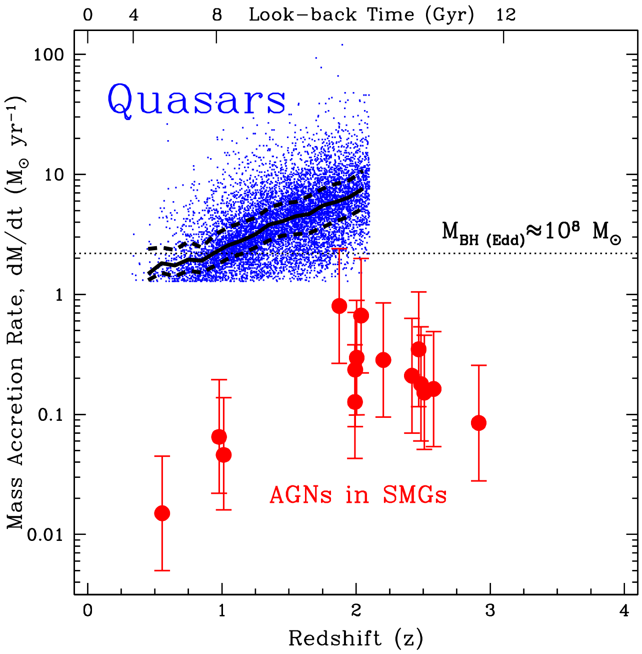

Figure 1. Black-hole mass accretion rates. SMGs (filled circles), and a comparison sample of $M_{\rm B} < -24$ quasars (dots) are shown[4]. The error bars represent the estimated uncertainty in the X-ray to bolometric correction for AGN activity in SMGs; see Table 1. The solid and dashed curves indicate the median and interquartile ranges for the comparison quasar sample. The dotted line indicates the approximate Eddington-limited mass accretion rate for an $\approx 10^8\ M_\odot$ black hole ($M_{\rm BH(Edd)}$). The SMGs have mass accretion rates approximately an order of magnitude lower than those of coeval quasars[4], suggesting that their black holes are smaller (typically $\approx 10^7$–$10^8\ M_\odot$); see text for additional black-hole mass constraints.

activity, but we note that at least one shows evidence for AGN activity at near-infrared wavelengths[16].

Two different observing modes were used in constructing the SMG sample: 14 of the radio sources were specifically targeted with SCUBA observations and 6 of the radio sources were detected in blank-field SCUBA maps. Although targeting known radio sources with SCUBA observations could potentially bias our AGN fraction owing to contributions to the radio emission from AGN activity, a statistical analysis does not reveal a strong AGN bias in our sample (P=1.0, two-sided Fisher's exact test); see Table 1 for the observing modes of the X-ray classified AGNs. However, due to the large positional uncertainties of SCUBA sources ($\approx$ 6–7 arcseconds), redshifts could not be obtained for the $\approx$ 35–50% of the radio-undetected SMG population, some of which might host AGN activity[6,9]. Making the conservative assumption that none of the radio-undetected SMGs hosts AGN activity, our X-ray data alone suggest an AGN fraction in the SMG population of $> 38^{+12}_{-10}\%$. We note that a similar fraction of comparably luminous galaxies in the local Universe host AGN activity[22], although their space density is approximately 3 orders of magnitude smaller than SMGs.

The large AGN fraction in the SMG population indicates that their black holes are growing almost continuously throughout the intense star-formation phase of these galaxies [i.e., assuming that all SMGs are growing their black holes, the AGN duty cycle is $> 38^{+12}_{-10}\%$]. This suggests that the black holes and galaxy spheroids are growing concordantly in SMGs[1]. Such a close association between AGN and star-formation activity is not seen in the coeval field galaxy population or other coeval star-forming galaxy populations ($\approx$ 3–15% AGN fraction)[23,24]. The almost continuous black-hole growth in SMGs suggests that there is an abundance of available fuel, hinting that the accretion may be occurring efficiently (i.e., at or close to the Eddington limit), as predicted by theoretical studies of the growth of massive black holes[25–27]. The majority ($\approx$ 85%) of the AGNs are obscured (see Table 1), as also predicted for black holes undergoing efficient growth[25].

The unobscured X-ray luminosities of the AGNs ($L_{\rm X} \approx 10^{43}$–$10^{44}$ erg s^{-1}) suggest that the mass accretion rates are modest ($\lesssim 1\ M_\odot$ yr^{-1}); see Table 1 and Figure 1. By comparison to coeval quasars, the mass accretion rates in SMGs are approximately an order of magnitude lower, also suggesting modest black-hole masses (i.e., $\approx 10^7$–$10^8\ M_\odot$; see Table 1 and Figure 1). Although these black-hole mass estimates are uncertain, the narrowness of the broad emission lines (BELs; typical full-width half maximum velocities of ≈ 2500 km s^{-1})[16], when they are visible, also suggest black-hole masses of $< 10^8\ M_\odot$ (ref 4). As well-studied AGNs with narrow BELs are found to be accreting at (or even beyond) the Eddington limit[4], this provides further support for the idea that the mass accretion rate in SMGs is approximately Eddington limited. Under the assumption of Eddington-limited accretion, the black holes in the SMGs will grow by up to an order of magnitude over their $\approx 10^8$ yr star-formation lifetime. These overall properties are consistent with those expected for massive galaxies undergoing rapid black-hole growth.

The total black-hole growth from SMGs can be calculated by integrating the average accretion density over the SMG redshift range; see Figure 2. Over the redshift interval z = 1.8–3.0 (corresponding to 80% of the SMGs studied here), the black-hole density produced by SMGs is $\approx 6^{+11}_{-4} \times 10^3\ M_\odot$ Mpc^{-3}. To put this quantity into context we need to compare it to the black-hole growth from coeval quasar activity. Considering only quasars in the luminosity range of $M_{\rm B}$ = –24 to –27 (the majority of which reside in $\gtrsim M_*$ spheroid-dominated galaxies[28] and have the properties consistent with being the progeny of SMGs[5]), the total SMG black-hole density is $\approx 13^{+27}_{-9}\%$ of the black-hole growth from quasar activity[2]. These constraints should be considered lower limits since further pre-quasar growth at z = 1.8–3.0 may be produced by radio-undetected SMGs and galaxies with fainter submillimetre fluxes, if they host AGN activity. However, these results are consistent with, for example, SMGs undergoing an intense black-hole growth phase, where the black hole is grown from $\approx 10^7$ to $\approx 10^8$ $M_\odot$, prior to a high accretion-rate quasar phase, where the black hole is grown from $\approx 10^8$ to $\approx 8 \times 10^8$ $M_\odot$. In this scenario, although SMGs do not produce a large fraction of the cosmological black-hole density, they are responsible for the crucial pre-quasar phase where the black holes in massive galaxies are rapidly grown. Indeed, the total black-hole growth from SMGs could only exceed that from quasar activity if the quasar lifetime is insufficient to double the mass of the black hole (i.e., $< 3 \times 10^7$ yrs assuming Eddington-limited accretion). Overall, this picture is in good agreement with direct theoretical predictions of the black-hole growth of SMGs and quasars[26,27].

What was the catalyst for the rapid black hole and stellar growth seen in SMGs? Rest-frame ultra-violet images taken by the *Hubble Space Telescope* have shown that a considerably larger fraction of SMGs are in major mergers (i.e., the merging of two galaxies of comparable masses) than has been found in the coeval galaxy population[17,29]. Hydrodynamical simulations have shown that major mergers can efficiently transport material toward the central regions of galaxies, providing an effective mechanism to trigger nuclear star formation and fuel the black hole[30]. The result of these major mergers is thought to be massive spheroid-dominated galaxies. Ultra-deep X-ray observations of SMGs undergoing major mergers have shown that AGN activity can be ongoing in both galactic components[12]. Presumably in these major-merger events the black holes will eventually coalesce, further increasing the mass of the black hole in the resultant galaxy.

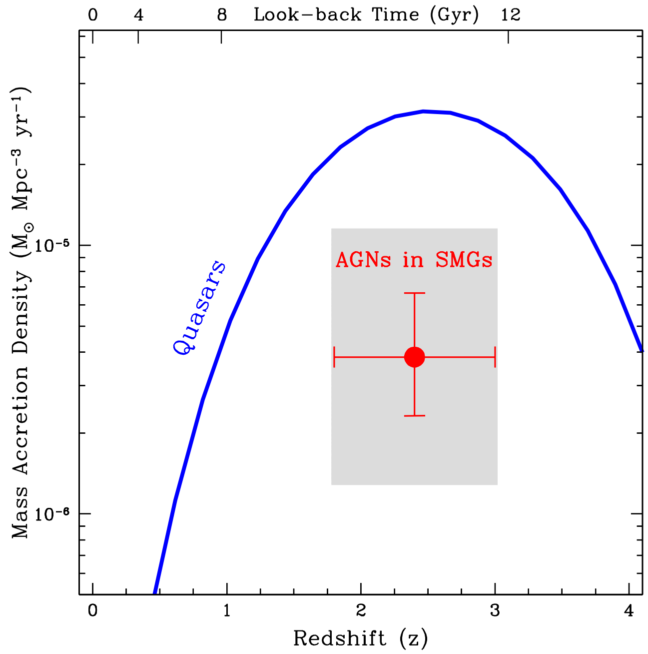

Figure 2. Cosmological black-hole accretion density. SMGs (filled circle), and $M_{\rm B} = -24$ to -27 quasars (solid line)[2] are shown. Error bars in the x-axis direction indicate the redshift range and error bars in the y-axis direction represent 1σ Poisson counting uncertainties. The shaded region indicates the uncertainty in the mass accretion rate conversion for the SMGs; see Table 1. The mass accretion density from SMGs is $\approx 13^{+27}_{-9}$% of that produced by coeval $M_{\rm B} = -24$ to -27 quasar activity over the redshift interval $z = 1.8$–3.0.

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Table 1. The Properties of the X-ray Classified AGNs

SMG name	$S_{850\mu m}$ (mJy)	z	$\log(L_X)$ (erg s^{-1})	$\log(L_{BOL})$ ($L_\odot$)	$\frac{dM}{dt}$ ($M_\odot$ yr^{-1})	$M_{BH(Edd)}$ (10^7 $M_\odot$)	X-ray Obscuration?	Observation Mode?
123549.4 +621536	8.3±2.5	2.20	44.0	12.9	$0.28^{+0.57}_{-0.19}$	$1.3^{+2.6}_{-0.9}$	Y	T
123555.1 +620901	5.4±1.9	1.88	44.4	13.2	$0.80^{+1.60}_{-0.53}$	$3.6^{+7.3}_{-2.4}$	Y	T
123606.7 +621550	4.4±1.4	2.42	43.8	12.6	$0.21^{+0.42}_{-0.14}$	$1.0^{+1.9}_{-0.6}$	N	M
123606.8 +621021	11.6±3.5	2.51	43.7	13.1	$0.15^{+0.31}_{-0.10}$	$0.7^{+1.4}_{-0.5}$	Y	T
123616.1 +621513	5.8±1.1	2.58	43.7	13.0	$0.16^{+0.33}_{-0.11}$	$0.7^{+1.5}_{-0.5}$	Y	T
123622.6 +621629	7.7±1.3	2.47	44.0	13.1	$0.35^{+0.70}_{-0.23}$	$1.6^{+3.2}_{-1.1}$	Y	T
123629.1 +621045	5.0±1.3	1.01	43.2	12.1	$0.05^{+0.09}_{-0.03}$	$0.2^{+0.4}_{-0.1}$	Y	T
123632.6 +620800	5.5±1.3	1.99	43.9	12.9	$0.24^{+0.47}_{-0.16}$	$1.1^{+2.2}_{-0.7}$	Y	M
123635.5 +621424	5.5±1.4	2.01	44.0	12.9	$0.30^{+0.60}_{-0.20}$	$1.4^{+2.7}_{-0.9}$	Y	T
123636.7 +621156	7.0±2.1	0.56	42.7	11.1	$0.02^{+0.03}_{-0.01}$	$0.1^{+0.1}_{-0.1}$	N	M
123707.2 +621408	4.7±1.5	2.48	43.8	12.9	$0.18^{+0.36}_{-0.12}$	$0.8^{+1.6}_{-0.5}$	Y	T
123711.9 +621325	4.2±1.4	1.99	43.6	12.7	$0.13^{+0.25}_{-0.08}$	$0.6^{+1.2}_{-0.4}$	Y	T
123712.0 +621212	8.0±1.8	2.91	43.4	12.7	$0.09^{+0.17}_{-0.06}$	$0.4^{+0.8}_{-0.3}$	Y	M
123716.0 +620323	5.3±1.7	2.04	44.3	13.0	$0.67^{+1.33}_{-0.44}$	$3.0^{+6.1}_{-2.0}$	Y	T
123721.8 +621035	12.0±3.9	0.98	43.7	11.7	$0.16^{+0.31}_{-0.10}$	$0.7^{+1.4}_{-0.5}$	Y	M

NOTES. — SMG name, submillimetre flux density ($S_{850\mu m}$), redshift (z), and total bolometric luminosity (L_{BOL}) are taken from ref 9. Unobscured rest-frame 0.5–8.0 keV luminosity (L_X), and the presence of X-ray obscuration ($N_H > 10^{22}$ cm^{-2}) are taken from ref 19. The observation mode refers to whether the source was specifically targeted with a SCUBA observation ("T") or whether the source was detected in a blank-field SCUBA map ("M"): 10 of the AGNs were identified in targeted SCUBA observations and 5 of the AGNs were identified in blank-field SCUBA maps. The mass accretion rate (dM/dt) is estimated by converting the X-ray luminosity to the AGN bolometric luminosity, under the assumption that the X-ray luminosity accounts for 6^{+12}_{-4}% of the bolometric luminosity of the AGN (i.e., the range in conversion factors found in ref 20). Although our assumed bolometric conversion factors were originally derived from unobscured AGNs, while the majority of the AGNs in our sample are obscured, the important issue is the relationship between the intrinsic X-ray emission and the ultraviolet-optical accretion disk emission, which is unlikely to be obscuration dependent. We also note that our bolometric conversion factors agree with those estimated for obscured AGNs with similar luminosities (and therefore similar mass accretion rates) to the sources studied here[3,21]. When converting from the bolometric luminosity to the accreted mass we assumed the canonical efficiency of 10% ($\epsilon = 0.1$). The black-hole mass ($M_{BH(Edd)}$) is calculated from the mass accretion rate under the assumption that the accretion is Eddington limited; see text for justification. The black-hole masses will be higher if the accretion is sub Eddington; see text for additional black-hole mass constraints.

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