Submillimeter Evidence for the Coeval Growth of Massive Black Holes and Galaxy Bulges

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The correlation, found in nearby galaxies, between black hole mass and stellar bulge mass implies that the formation of these two components must be related. Here we report submillimeter photometry of eight x–ray absorbed active galactic nuclei which have luminosities and redshifts characteristic of the sources that produce the bulk of the accretion luminosity in the universe. The four sources with the highest redshifts are detected at 850 microns, with flux densities between 5.9 and 10.1 milliJanskies, and hence are ultraluminous infrared galaxies. Interpreting the submillimeter flux as emission from dust heated by starbursts, these results suggest that the majority of stars in spheroids were formed at the same time as their central black holes built up most of their mass by accretion, accounting for the observed demography of massive black holes in the local universe. The skewed rate of submillimeter detection with redshift is consistent with a high redshift epoch of star formation in radio quiet active galactic nuclei, similar to that seen in radio galaxies.

In the local universe, central black holes are found in most galaxy spheroids (a collective term for elliptical galaxies and the bulges of spiral galaxies) with mass roughly proportional to that of the spheroid (0.13% ±0.4 dex) (*1*). The simplest explanation for this proportionality is that the black hole mass is built up in active galactic nuclei (AGN) by accretion of the same gas that is rapidly forming the stars which make up the spheroid, i.e. the formation of the spheroid and the growth of the massive black hole are coeval. Assuming that 10% of the spheroid mass M is converted from hydrogen to helium in stars (*2*) at an efficiency of 0.007 and radiated, and that 0.13% of the spheroid mass M is accreted by the central black hole (*1*) at 10% efficiency, the ratio of radiation emitted by the starburst (E_{SB}) to that emitted by the AGN (E_{AGN})is:

$$\frac{E_{SB}}{E_{AGN}} = \frac{0.1M \times 0.007}{0.0013M \times 0.1} \sim 5 \quad (1)$$

and hence if they have similar lifetimes we expect the stellar component to have around 5 times the bolometric luminosity of the AGN during the spheroid formation; a similar argument has been used to estimate the relative contribution of accretion and nuclear fusion to the extragalactic background radiation (*3*). The scatter on this relation for individual objects is expected to be at least 0.4 dex to account for the scatter on the present day spheroid/black hole mass ratio (*1*), with additional scatter of $\sim$ 0.3 dex from the intrinsic variability of each AGN (*4*).

To investigate this hypothesis, we have studied a sample of eight $z > 1$, x–ray absorbed AGN discovered serendipitously in archival x–ray data (Table 1). They were chosen from the fourteen such sources reported (*5*) on the basis of visibility in our allocated observing shifts at the James Clerk Maxwell Telescope (JCMT). If the stellar and black hole components of present day galaxy spheroids did form at the same time, then the majority of star formation in spheroids must have taken place around the AGN that dominate the universe's accretion power, i.e. those that are responsible for the majority of present-day black hole mass. Our targets are representative of these AGN for four reasons. Firstly, their redshifts span the $1 < z < 3$ epoch in which the accretion luminosity from AGN peaked. For example in the best fit luminosity function of a large sample of x–ray selected AGN (*6*), the comoving AGN x–ray luminosity density is more than a factor 10 larger at $z = 2$ than in the local universe. Secondly, their luminosities are close to the break in the luminosity function, which is where the majority of AGN accretion luminosity is produced. For example in the same model x–ray luminosity function (*6*), 60% of the comoving AGN x–ray luminosity density is produced by AGN within ± 0.5 dex of the break in the luminosity function, which is at $\log L_X = 44.5$ at $z = 2$. Thirdly, they are x–ray absorbed sources. It has been estimated (*7*) that 85% of accretion power in the universe is absorbed, and x–ray background synthesis models require that the majority of AGN are intrinsically absorbed (*8*). Finally, most of them (all but one) are radio quiet; close to the break in the luminosity function, radio quiet AGN outnumber radio loud AGN by about 15:1 (*9*).

Observations at 850μm were carried out at the JCMT in excellent, stable weather conditions (*10*) on the 18th – 20th January 2001 using the Submillimeter Common User Bolometer Array (SCUBA) (*11*). Four of the eight sources have significant detections ($> 5\sigma$) at 850μm with flux densities between 5.9 and 10.1 mJy; the other four sources were not detected (Table 1). The high submillimeter detection rate for our sources (50%) contrasts with the low rates of detection ($\leq$ 10%) in previous submillimeter surveys of x–ray selected objects (*12–16*). However, the x–ray sources investigated here have significantly higher x–ray flux (by more than a factor of 3) than the relatively faint x–ray sources in the other surveys, and hence the faint x–ray sources would probably not be detectable at 850μm even if they had the same ratio of submillimeter to x–ray flux as our 850 μm detected sources. Although our sample is small, our high detection rate means that at the 99% confidence level $> 12\%$ (*16*) of the population from which our sample was drawn are 850μm sources detectable with SCUBA; at the 95% confidence level this figure rises to $> 19\%$.

We interpret the observed submillimeter flux from all our sources as thermal emission from dust. Because RXJ163308.57+570258.7 is radio loud (*5*), we have also considered (but rejected) the possibility that synchrotron emission contributes to the flux from this source at submillimeter wavelengths. The source has a 1.4 GHz flux density of 17.2±0.7 mJy in the northern Very Large Array sky survey (*17*) and a 325 MHz flux density of 78±4 mJy in the Westerbork northern sky survey (*18*). It is therefore a steep spectrum source and extrapolating the spectrum as a power law we expect it to contribute an insignificant amount (< 0.1 mJy) at 850μm. We therefore conclude that the observed 850μm flux of RXJ163308.57+570258.7 is dominated by thermal emission from dust. For all our sources, we have estimated the total far infrared (FIR) luminosities L_{FIR} and dust masses M_d (Table 1) from the monochromatic 850μm fluxes using the FIR spectrum of Mrk 231 as a template. Mrk 231 is appropriate because it is a well studied, nearby ultraluminous infrared galaxy (ULIRG), which is similar to our AGN in that it hosts an x–ray absorbed, broad line, active nucleus, and has similar submillimeter luminosity (see Fig. 1). We have fitted an isothermal optically thin dust model (*19*) to the FIR data on Mrk 231 (*20*) and obtained a good fit for dust temperature $T = 44$ K, β=1.55 (where β is the power law index of the frequency dependence of the dust emissivity) and FIR luminosity of 3.9×10^{12} $L_{\odot}$. The FIR luminosities of the four detected AGN qualify them as ULIRGs, and the FIR luminosity of RXJ094144.51+385434.8 in particular is sufficient for it to be classed as a 'hyperluminous' infrared galaxy (*21*). The current upper limits to the submillimeter fluxes of the four undetected AGN are larger than the flux expected from Mrk 231 at equivalent redshifts (Fig. 1), and it is therefore possible that the entire sample could be ULIRGs.

An important question is the relative contribution of AGN-heated and starburst-heated dust to the FIR luminosities of ULIRGs. Recent results from *ISO* mid-infrared spectroscopy (*22*), millimeter interferometry (*23*) and detailed radiative transfer modeling (*21*) suggest that massive stars are the dominant power source of around three quarters of nearby ULIRGs (including Mrk 231) and hyperluminous infrared galaxies. For our four sources detected at 850μm, comparing the power output of the AGN to the power emitted in the FIR gives an indication of the relative importance of AGN and starburst heating of the FIR emitting dust. Assuming that 3% of the bolometric luminosity of an AGN is emitted in the 0.5 - 2 keV band (*24*,*25*), the bolometric luminosities of the AGN in RXJ094144.51+385434.8 and RXJ121803.82+470854.6 are about one quarter and one third of their FIR luminosities respectively, while the AGN and FIR luminosities are equivalent (within 0.1 dex) in RXJ124913.86-055906.2 and RXJ163308.57+570258.7. This means that in RXJ094144.51+385434.8 and RXJ121803.82+470854.6 the AGN are not sufficiently powerful to heat the FIR emitting dust, while in the other two cases all of the AGN radiation would have to be absorbed and re-emitted by dust for the AGN to power the FIR emission. The low ratios of AGN to FIR luminosity therefore make it very likely that in these sources the FIR is predominantly powered by starlight rather than the central AGN. Our submillimeter detections thus imply that these sources contain massive reservoirs of molecular gas and are producing stars at a prodigious rate ($> 1000\ M_{\odot}\ \mathrm{yr}^{-1}$).

These results have important implications for our understanding of the formation of galaxy spheroids and massive black holes. The four AGN we have detected at 850μm all have FIR and AGN luminosities similar to what would be expected from equation 1 (this could also be true for the four sources undetected at 850μm: this possibility is not excluded by the current 850μm upper limits). Our 850μm detection rate thus implies that with 95% confidence, between 19% and 100% of the the population from which our sample is drawn are simultaneously building up their black hole mass by accretion and undergoing intense star formation at rates which are consistent with, indeed suggestive of, the spheroid/AGN formation scenario outlined at the beginning of this letter.

The redshift distribution of our detections is bimodal, in that all the sources with $z > 1.5$ have been detected at 850μm compared to none of the sources with $z < 1.5$. This is unlikely to be coincidence: if we split the sample in two by redshift, and assume that the underlying probability of submillimeter detection were independent of redshift, then the probability of detecting all the sources in one redshift bin and detecting none of the sources in the other is $< 1\%$. However, the two highest redshift objects in the sample also have the highest x–ray luminosities, and hence a correlation between x–ray and submillimeter luminosity could be responsible for the bimodal detection rate. Nonetheless, the skewed detection rate is in the same sense as the strong dependence of submillimeter luminosity with redshift that has already been found in a sample of radio galaxies (*26*), suggesting that radio galaxies had higher rates of star formation at earlier epochs. Age determinations of stellar bulges in nearby luminous AGN suggest that radio quiet AGN, as well as radio loud AGN, had higher rates of star formation at earlier epochs (*27*); the trend seen in our data is consistent with this hypothesis.

A consequence of coeval spheroid and black hole formation for the recently discovered luminous submillimeter population (*28*), would be that the majority must host AGN. Indeed, it is already known that a significant fraction of the most luminous submillimeter galaxies found so far in deep SCUBA surveys contain AGN (*29*). At redshifts of 2 – 3, starbursts with similar bolometric luminosity to AGN with $44 < \log L_X < 45$ would have 850μm fluxes of $\sim 0.5 - 5$ mJy, and this is the flux range in which the bulk of the cosmic 850μm background is produced (*30*). Current x–ray luminosity functions (*6*,*31*) suggest that there are at least several hundreds of AGN deg^{-2} with $z > 1$ and $\log L_X > 44$ assuming a 4:1 ratio of obscured to unobscured sources. Although this falls well short of the current 850μm source counts (8000$\pm$3000 deg^{-2} at 1 mJy) (*30*), the AGN x–ray luminosity function has a large uncertainty at $z > 2$, which is the epoch in which the majority of luminous submillimeter galaxies are found (*32*). Furthermore, the space density of obscured AGN at high redshift is unknown: the x–ray background intensity does not preclude the existence of a large population of high redshift Compton-thick sources.

1 References and notes

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Table 1: Characteristics of the observed x–ray absorbed AGN and their observed submillimeter emission. We assume a Hubble constant $H_0 = 50$ km s^{-1} Mpc^{-1}, a deceleration parameter $q_0 = 0.5$ and zero cosmological constant. For sources that were not detected with SCUBA we have estimated upper limits to L_{FIR} and M_d by taking the upper limit of S_{850} to be S_{850} $+2\sigma$ for sources with positive S_{850}, and 2σ for sources with negative S_{850}.

1	2	3	4	5	6	7	8	9
Source	z	S_X	log L_X	log N_H	RL/RQ	S_{850} (mJy)	Dust Mass ($M_\odot$)	L_{FIR} ($L_\odot$)
RXJ094144.51+385434.8	1.819	$2.1^{+0.5}_{-0.5}$	44.8 ± 0.1	$21.9^{+0.5}_{-0.4}$	RQ	10.1 ± 1.7	1.2×10^9	2.0×10^{13}
RXJ101123.17+524912.4	1.012	$3.3^{+1.0}_{-0.9}$	44.7 ± 0.2	$22.5^{+0.2}_{-0.3}$	RQ	-1.4 ± 1.9	$< 4.7 \times 10^8$	$< 8.0 \times 10^{12}$
RXJ104723.37+540412.6	1.500	$1.7^{+0.7}_{-0.6}$	44.6 ± 0.2	$22.2^{+0.4}_{-0.6}$	RQ	2.3 ± 1.8	$< 7.2 \times 10^8$	$< 1.2 \times 10^{13}$
RXJ111942.16+211518.1	1.288	$3.4^{+0.6}_{-0.5}$	44.6 ± 0.1	$21.4^{+0.4}_{-0.3}$	RQ	-0.9 ± 1.8	$< 4.5 \times 10^8$	$< 7.6 \times 10^{12}$
RXJ121803.82+470854.6	1.743	$1.5^{+0.4}_{-0.4}$	44.7 ± 0.2	$22.3^{+0.3}_{-0.7}$	RQ	6.8 ± 1.2	8.0×10^8	1.4×10^{13}
RXJ124913.86−055906.2	2.212	$2.4^{+0.5}_{-0.4}$	45.1 ± 0.1	$22.2^{+0.4}_{-0.6}$	RQ	7.2 ± 1.4	7.8×10^8	1.3×10^{13}
RXJ135529.59+182413.6	1.196	$3.6^{+0.9}_{-0.9}$	44.7 ± 0.2	$22.2^{+0.2}_{-0.5}$	RQ	0.8 ± 1.3	$< 4.3 \times 10^8$	$< 7.2 \times 10^{12}$
RXJ163308.57+570258.7	2.802	$1.9^{+0.3}_{-0.3}$	45.2 ± 0.1	$22.5^{+0.3}_{-0.5}$	RL	5.9 ± 1.1	5.8×10^8	9.8×10^{12}

1 Source name based on *Rosat* position. RXJ124913.86−055906.2 is also known as [HB89] 1246−057, RXJ135529.59+182413.6 is also known as RIXOS F268_011, and RXJ163308.57+570258.7 is also known as WN B1632+5709

2 Redshift

3 Observed 0.5 – 2 keV flux (10^{-14} erg cm^{-2} s^{-1})

4 Log [0.5 – 2 keV luminosity (erg s^{-1})] corrected for intrinsic absorption

5 Log [intrinsic column density (cm^{-2})]

6 Radio loud (RL) if $\alpha_{OR} > 0.35$ or radio quiet (RQ) if $\alpha_{OR} < 0.35$

7 850μm flux. The quoted errors do not include calibration uncertainties of 10%.

8 Dust mass inferred from 850μm flux, adopting a value for the dust mass absorption coefficient (*33*) $\kappa_{100\mu m} = 5.5$ m^2 kg^{-1}

9 FIR luminosity inferred from 850μm flux

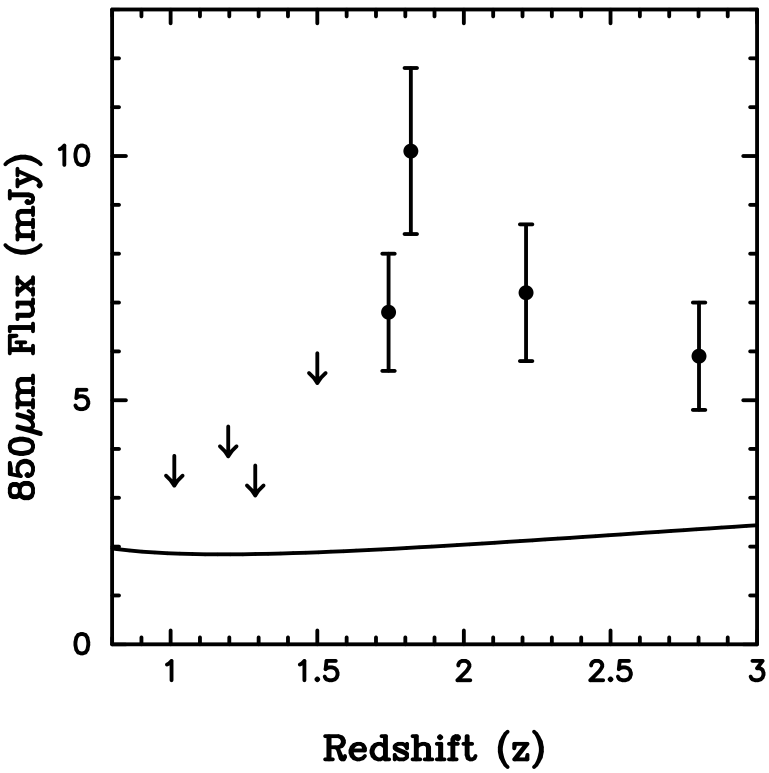

Figure 1: 850μm fluxes of the X-ray absorbed AGN as a function of redshift z. The solid line shows the predicted 850μm flux of Mrk 231 if it were viewed at redshift z.