Identifying the Obscured Black-Hole Growth Phase of Distant Massive Galaxies

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Abstract. It is well established that a dominant phase in the growth of massive galaxies occurred at high redshift and was heavily obscured by gas and dust. Many studies have explored the stellar growth of massive galaxies but few have combined these constraints with the growth of the supermassive black hole (SMBH; i.e., identified as AGN activity). In this brief contribution we highlight our work aimed at identifying AGNs in $z \approx 2$ luminous dust-obscured galaxies. Using both sensitive X-ray and infrared (IR)–sub millimeter (submm) observations, we show that AGN activity is common in $z \approx 2$ dust-obscured systems. With a variety of techniques we have found that the majority of the AGN activity is heavily obscured, and construct diagnostics based on X-ray–IR data to identify some of the most heavily obscured AGNs in the Universe (i.e., AGNs obscured by Compton-thick material; $N_H > 1.5 \times 10^{24}$ cm$^{-2}$). On the basis of these techniques we show that SMBH growth was typically heavily obscured ($N_H \geq 10^{23}$ cm$^{-2}$) at $z \approx 2$, and find that the growth of the SMBH and spheroid was closely connected, even in the most rapidly evolving systems.

1. Introduction

There is no doubt that Active Galactic Nuclei (AGN) are an important component in the formation and evolution of galaxies. The seminal discovery that massive galaxies in the local Universe harbor a super-massive black hole (SMBH) indicates that they must have hosted AGN activity over the past $\approx 13$ Gyrs (e.g., Soltan 1982; Kormendy & Richstone 1995). Furthermore, the close relationship between the mass of the SMBH and the spheroid in local galaxies points towards a close connection between the growth of the SMBH and the host galaxy (e.g., Magorrian et al. 1998; Ferrarese & Merritt 2000). Finally, the most successful galaxy formation and large-scale structure models require AGN outflows to suppress star formation and reproduce the properties of massive galaxies in the local Universe (e.g., Croton et al. 2006; Bower et al. 2006).

Stellar population synthesis modelling of nearby galaxies and studies of the cosmic history of star formation indicate that the bulk of the stellar build up of massive galaxies must have occurred at high redshift ($z \approx 2$; i.e., when the Universe was $\approx 25\%$ the current age; e.g., Heavens et al. 2004; Hopkins et al. 2006). Under the assumption that the growth of the SMBH is concordant with that of the galaxy spheroid, the dominant growth phase of SMBH growth in massive galaxies must also have occurred at high redshift. Currently the most efficient identification of AGNs (and therefore SMBH growth) is made with deep X-ray surveys (e.g., Brandt & Hasinger 2005). For example, the deepest X-ray surveys (e.g., Alexander et al. 2003; Luo et al. 2008) are able to detect even
moderately luminous AGN activity at \( z \approx 2 \) (\( L_X \approx 10^{42} - 10^{43} \text{ erg s}^{-1} \); i.e., > 10 times below the canonical threshold assumed for quasars). Furthermore, the high rest-frame energies probed by these surveys at \( z \approx 2 \) (\( \approx 1.5 - 24 \text{ keV} \)) means that the selection of AGNs is almost obscuration independent. This latter point is important since the dominant growth phase of massive galaxies appears to have been heavily obscured by dust and gas (e.g., Chapman et al. 2005; Le Floc’h et al. 2005).

In this brief contribution we highlight some of our recent work aimed at identifying obscured AGN activity in distant rapidly evolving galaxies at \( z \approx 2 \); see §2 & §3. We discuss these results within the context of the SMBH–spheroid growth phase of today’s massive galaxies (\( M_{\text{GAL}} \approx 10^{11} M_\odot \)); see §4.

### 2. Heavily Obscured Black-Hole Growth in the Most Luminous \( z \approx 2 \) Galaxies

Due to the negative \( K \)-correction for IR-luminous galaxies at \( z > 1 \), submm/mm surveys select the most bolometrically luminous systems in the Universe (e.g., Blain et al. 2002; \( L_{\text{BOL}} \approx 10^{43} L_\odot \)). After intense multi-wavelength follow-up observations it is now clear that submm-emitting galaxies (SMGs; \( f_{850\mu m} > 4 \text{ mJy} \)) are gas-rich massive galaxies at \( z \approx 2 \) hosting energetic star-formation activity (e.g., Smail et al. 2002; 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 possible that every massive galaxy (\( > 1–3 L_\ast \)) in the local Universe underwent at least one submm-bright phase at some time in the distant past (e.g., Swinbank et al. 2006). It is therefore interesting to ask the question: do these intense starbursts also host AGN activity?

Early comparisons between X-ray and submm surveys showed little overlap between the two populations. However, using the deepest X-ray observations available (the 2 Ms Chandra Deep Field-North survey; Alexander et al. 2003), we found that a large fraction (\( \approx 28–50\% \)) of SMGs host X-ray weak AGN activity (Alexander et al. 2005a). With X-ray color-color diagnostics the amount of absorption towards the AGN in individual SMGs could be assessed. By stacking the X-ray data of AGNs with the same apparent amount of absorption, it was then possible to construct good-quality composite X-ray spectra, allowing the definitive features of X-ray absorption to be identified (photo-electric absorption cut off; possible Fe Kα emission); see Fig. 1. These analyses indicate that the majority (\( \approx 85\% \)) of the AGNs in SMGs are heavily obscured (\( N_H \geq 10^{23} \text{ cm}^{-2} \)) and some may be Compton thick (\( N_H > 1.5 \times 10^{24} \text{ cm}^{-2} \)); see §3 for other constraints on Compton-thick AGNs. However, even correcting for the presence of absorption, the AGN activity in SMGs was typically found to be of moderate luminosity (\( L_X \approx 10^{43} - 10^{44} \text{ erg s}^{-1} \)). Given the huge bolometric luminosities of these systems, we suggested that, although AGN activity is often present, star formation is likely to dominate the energetics of SMGs. Spitzer-IRS observations have indeed shown that the mid-IR spectra of SMGs are dominated by star-
Figure 1. Composite rest-frame 2–20 keV spectra for the $z \approx 2$ SMGs hosting AGN activity in Alexander et al. (2005b). AGNs with comparable amounts of X-ray absorption have been stacked in rest-frame energy space; as indicated. The majority ($\approx 85\%$) of the AGNs are heavily obscured ($N_H \geq 10^{23}$ cm$^{-2}$) and some may be Compton thick ($N_H > 1.5 \times 10^{24}$ cm$^{-2}$). See Fig. 7 of Alexander et al. (2005b) for more details.

formation activity, but often have an underlying continuum component of AGN activity (e.g., Menendez-Delmestre et al. 2007; Pope et al. 2008).

3. Identification of a Large Population of Compton-thick Quasars at $z \approx 2$

The majority of the AGNs identified in the SMG population are obscured. However, even with a 2 Ms Chandra exposure, the most heavily obscured AGNs can be weak or undetected at X-ray energies. The most challenging sources to identify are Compton-thick AGNs with $N_H > 1.5 \times 10^{24}$ cm$^{-2}$. In the local Universe, Compton-thick AGNs comprise $\approx 50\%$ of the AGN population (e.g.,
Risaliti et al. (1999) and, given claims of a possible increase in AGN obscuration with redshift (e.g., La Franca et al. 2005), it is expected that at least $\approx 50\%$ of the distant AGN population will also be Compton thick. The most robust identification of Compton-thick AGNs is made with X-ray spectroscopy, where the presence of a high equivalent width Fe K emission line and a steeply rising reflection component at $> 10$ keV reveals that little or no X-ray emission is being seen directly (e.g., George & Fabian 1991). However, the extreme absorption towards a Compton-thick AGN renders the observed X-ray emission orders of magnitude fainter than the intrinsic emission (i.e., the emission corrected for absorption). For example, the nearby well-studied AGN NGC 1068 has an intrinsic X-ray luminosity comparable to AGNs identified in SMGs but, due to the presence of extreme absorption ($N_H \approx 10^{25}$ cm$^{-2}$; i.e., heavily Compton thick), if placed at $z \approx 2$ it would have an estimated flux $\approx 10$ times below the sensitivity limit of the 2 Ms CDF-N observations. This illustrates the considerable challenges in identifying distant Compton-thick AGNs.

Clearly, in order to be able to provide a complete census of AGN activity (and therefore the cosmic history of SMBH growth) it is necessary to be able to identify such heavily obscured AGNs without the need for high-quality X-ray spectroscopy; the latter will be challenging before the next generation of X-ray observatories, requiring $\gg 10$ Ms X-ray exposures.

Significant progress in the identification of X-ray undetected (potentially Compton thick) AGNs has been made using Spitzer observations of $z \approx 2$ massive galaxies (e.g., Daddi et al. 2007; Fiore et al. 2008). For example, selecting galaxies with excess IR emission over that expected from star-formation activity (on the basis of absorption-corrected UV emission), Daddi et al. (2007) revealed a large population of X-ray undetected IR-luminous galaxies with either extreme dust-obscured star formation or AGN activity. Using X-ray stacking analyses, Daddi et al. (2007) showed that, although individual galaxies were not detected in the X-ray band, the average stacked X-ray spectral slope is flat ($\Gamma \approx 0.9$). Such a flat X-ray spectral slope unambiguously indicates the presence of heavily obscured AGN activity in many systems, some of which may be obscured by Compton-thick material.

The work of Daddi et al. (2007) and Fiore et al. (2008) undoubtedly provide important constraints on the space density of the most heavily obscured AGNs, and therefore of the most heavily obscured phases of SMBH growth. However, since these studies were based on X-ray stacking analyses there are significant uncertainties on (1) the fraction of obscured AGNs that are contributing to the stacked hard X-ray spectral slope (e.g., Donley et al. 2008), (2) the intrinsic luminosities of the AGNs, and (3) the fraction of the AGNs that are Compton thick, since both Compton-thin and Compton-thick AGNs can have flat X-ray spectral slopes. Using the latest 2 Ms Chandra observations of the CDF-S (Luo et al. 2008), we have been able to place constraints on issues (1) and (2) by detecting individual AGNs that were contributing to the stack in Daddi et al. (2007). This new analysis has shown that the fraction of obscured AGNs contributing to the X-ray stacking results is at least $\approx 25\%$, and that the AGNs

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1Indeed, only $\approx 50$ Compton-thick AGNs have been robustly identified in the Universe, most at low redshift, a paltry $\approx 10^{-9}$ of the cosmic population (Comastri 2004)!
Figure 2. Diagnostic diagram for the identification of Compton-thick AGNs. X-ray luminosity (uncorrected for absorption) is plotted against the 6 $\mu$m AGN luminosity, obtained using either mid-IR spectroscopy or mid-IR spectral energy distributions. The intrinsic (absorption corrected) AGN luminosity is inferred from both the mid-IR AGN component and UV emission lines (as indicated). The plotted AGNs lie at $z \approx 2$ and have mid-IR and emission-line luminosities indicating AGN activity $\approx 2$–$3$ orders of magnitude higher than indicated by the X-ray luminosity: these are the signatures of a Compton-thick AGN. See Fig. 4 of Alexander et al. (2008b) for more details.

have a broad range of luminosities from $\approx 10^{42} - 10^{44}$ erg s$^{-1}$ (Alexander et al. 2009). However, without spectroscopic data, none of these studies are able to reliably determine how many of the AGNs are Compton thick (issue 3).

The robust identification of distant Compton-thick AGNs requires good quality spectra in addition to continuum observations. In Alexander et al. (2008b) we made great strides in this direction by identifying luminous AGNs in seven X-ray weak/undetected $z \approx 2$ galaxies with AGN signatures from optical and/or mid-IR ($Spitzer$-IRS) spectroscopy. The intrinsic X-ray luminosity of the AGNs in these galaxies could be estimated both from AGN-dominated optical
emission lines and AGN-dominated mid-IR emission (distinguished from star formation processes using mid-IR spectroscopy), giving $L_X \approx 10^{44} - 10^{45}$ erg s$^{-1}$ (i.e., luminous AGN activity). By comparison, the observed X-ray luminosities are $\approx 2$–$3$ orders of magnitude lower than those predicted, indicating that the X-ray emission must be obscured by Compton-thick material; see Fig. 2 and §3 in Alexander et al. (2008b). With these diagnostics it is therefore possible to identify distant Compton-thick AGNs in the absence of good-quality X-ray spectroscopy. Although limited in source statistics, the Alexander et al. (2008b) study was also able to place basic constraints on the space density of luminous Compton-thick AGNs ($L_X > 10^{44}$ erg s$^{-1}$) at $z \approx 2$–$2.5$. The derived space density of $(0.7$–$2.5) \times 10^{-5}$ Mpc$^{-3}$ is consistent with that found for comparably luminous unobscured AGNs, indicating that Compton-thick SMBH growth was as ubiquitous as unobscured SMBH growth in the distant Universe. However, since our method relied on the identification of optical emission lines, these constraints should be considered a lower limit on the Compton-thick AGN space density as there are likely to also be many Compton-thick AGNs with weak optical emission lines (e.g., NGC 6240 in the local Universe).

The Compton-thick AGNs spectroscopically identified in Alexander et al. (2008b) are more luminous than the AGNs studied in Daddi et al. (2007) and Fiore et al. (2008). However, this is clearly a selection effect since in order to infer that the X-ray emission from the AGNs in Alexander et al. (2008b) is obscured by Compton-thick material, it was necessary to select the most luminous AGNs; i.e., given an X-ray sensitivity limit of $\approx 10^{42}$–$10^{43}$ erg s$^{-1}$, only objects with intrinsic X-ray luminosities $> 10^{44}$ erg s$^{-1}$ could be reliably identified as Compton thick.

4. Joint Black-Hole–Galaxy Growth in $z \approx 2$ Galaxies

From a combination of X-ray, IR, and submm data with optical and mid-IR spectroscopy, we have been able to provide sensitive constraints on the ubiquity and properties of AGN activity in $z \approx 2$ dust-obscured galaxies. Can we use these constraints along with other multi-wavelength data to understand the relative SMBH–stellar growth in $z \approx 2$ galaxies? Interestingly we can.

The deep multi-wavelength of SMGs show that these $z \approx 2$ galaxies host both heavily obscured AGN and star formation activity; see §2. Qualitatively, this joint SMBH–stellar growth is consistent with that expected given the SMBH–spheroid mass relationship in the local Universe. However, constraints on the masses of the SMBH and spheroid suggest that the SMBHs in SMGs may be smaller than that expected given the local SMBH–spheroid mass constraints, indicating that the SMBH may be “catching up” with the growth of the SMBH (see Alexander et al. 2008a). The estimated growth rate of the SMBHs in SMGs do not appear to be sufficient to significantly overcome the growth rate of the spheroid, indicating that a more AGN-dominated growth phase may be required to place SMGs (and their progeny) on the locally defined SMBH–spheroid mass relationship (e.g., an optically bright quasar; Coppin et al. 2008). Although these constraints suggest that there is a “lag” in the SMBH growth in SMGs, given that SMGs are amongst the most rapidly evolving galaxies in the Universe, it is perhaps surprising that the relative SMBH–galaxy spheroid growth rate in
these systems is even approximately in agreement with that expected from the SMBH–spheroid mass relationship. This may indicate that some kind of regulatory mechanism is at work to “control” the growth of these two components (i.e., energetic winds/outflows).

The constraints on the SMBH–galaxy growth in the $z \approx 2$ Spitzer-detected galaxies studied by Daddi et al. (2007) are weaker than those determined for $z \approx 2$ SMGs since they are typically less luminous (and therefore fainter). However, based on the analyses of Daddi et al. (2007) and Murphy et al. (2009), there is clear evidence for both AGN activity and star formation in many of these systems. By decomposing the IR spectral energy distributions of the Spitzer-detected galaxies into AGN and star-formation components, Daddi et al. (2007) estimated that the volume averaged SMBH–stellar growth in these galaxies is consistent with that expected given the local SMBH–spheroid mass relationship. The $z \approx 2$ Spitzer-detected galaxies are growing less rapidly than the $z \approx 2$ SMGs, and are therefore are less likely to be able to significantly deviate from the local SMBH–spheroid mass relationship. However, it is perhaps remarkable that the relative SMBH–stellar growth rates of both populations are comparable.

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