THE *XMM-NEWTON* AND *SPITZER* VIEW OF GALAXY/AGN FORMATION AT $Z = 2 - 3$

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ABSTRACT

The genesis of spheroids is central to our understanding of galaxy formation. They contain half of the stellar mass of the Universe, and almost all of the black hole mass. According to galaxy formation models, cluster ellipticals form in high density regions through hierarchical merging of gas-rich subcomponents at early epochs. We have used X-ray absorbed QSOs at z 2-3 to signpost these regions, and found 2 proto-clusters of ultraluminous starburst galaxies using submm observations. If these objects are to evolve into elliptical galaxies, they should contain growing massive black holes. These regions of widespread collapse therefore represent a unique laboratory within which we can study the complete sequence of early AGN evolution.

As part of a detailed multiwavelength ongoing programme, we have used XMM-Newton and Spitzer to search for these buried AGN, and determine the evolutionary stage of the galaxies in the proto-clusters. Our observations provide a powerful test for models of black hole growth in galaxy bulges.

Key words: X-rays; submillimetre; Galaxies: active; Star formation.

1. INTRODUCTION

There is mounting evidence in favour of a physical relationship between the growth of the spheroids of galaxies through star formation and the growth of supermassive black holes (SMBH) through accretion: most (if not all) galaxies seem to host a supermassive black hole (Yu & Tremaine 2002), and the mass of the galaxy spheroid and the mass of the SMBH are strongly correlated (Merritt & Ferrarese 2001). The cosmic evolutions of the star formation and AGN emissivity follow similar trends, growing from $z = 0$ to $z \sim 2$, and then stabilizing or decreasing (the so called Madau plot, see e.g. Silverman et al. 2005). All this evidence shows that supermassive black holes may be a natural by-product (even a necessary one) in the process of galaxy formation.

In this context, direct studies of objects in the process of building simultaneously their star populations and their central SMBH are essential in order to understand the mechanisms involved, and the possible feedback effects.

Star formation is normally associated with thick molecular clouds that absorbs most of the UV-optical-NIR radiation, which is re-emited in the FIR-submm where it escapes unimpeded from all but the thickest environments. This has been confirmed by the detection of Ultra and Hyper Luminous Infrared Galaxies (ULIRG and HLIRG, respectively) by *IRAS*, in which star formation seems to dominate the bolometric emission, although it is uncertain how many of them are also AGN powered (Sanders & Mirabel 1996, Rowan-Robinson 2000). The K-correction at 850 μm is strongly negative for thermal dust sources, cancelling the cosmological dimming (Blain & Longair 1993). The transparency of the star forming environment, and the negative K-correction, favour strongly the FIR and the submm as the spectral windows with which to study star formation over the course of cosmic history.

Accretion onto SMBH produces copious X-ray emission, the hardest part of which (at energies above 2-10 keV) can also escape from very obscured environments. The presence of such very heavily obscured AGN is required by the spectrum of the X-ray Background (XRB, Fabian & Iwasawa 1999), and is assumed by all models for the XRB (Gilli et al. 2001), which also require that most accretion power in Universe is absorbed. Indeed, some of them even identify the material responsible for the X-ray absorption as strongly star-forming material (Fabian et al. 1998).

It is then clear that a combination of FIR/submm and hard X-ray observations has the potential to yield direct insights into the very core of the star forming and BH feeding regions, helping to quantify their mutual relationship. Here, we report our work in the past few years on submm, mid-IR, near IR, optical and X-ray observations of a sample of QSOs. In Section 2 we define the sam-

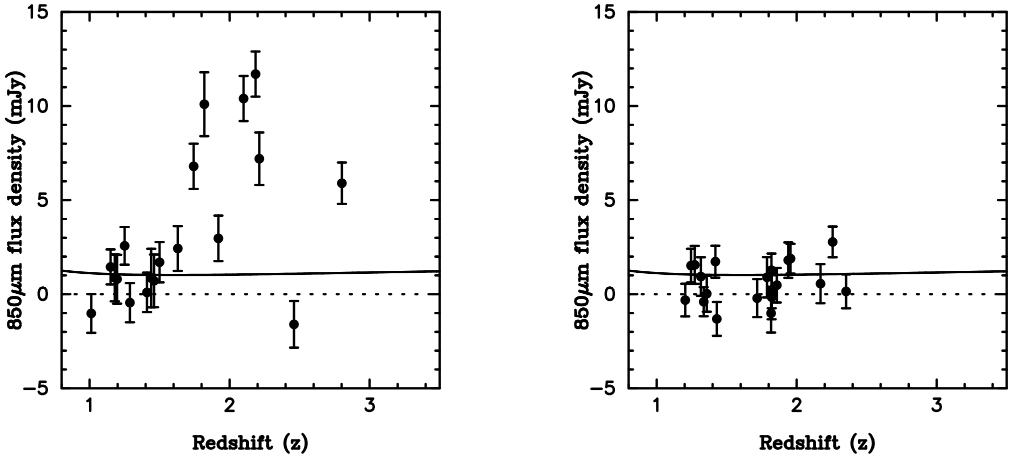

Figure 1. 850 μm flux vs. z for our sample of 19 X-ray absorbed (left) and unabsorbed (right) QSOs. The solid line is the expected flux from Mrk 231 (a nearby submm luminous X-ray absorbed QSO) if it were viewed at redshift z

ples of X-ray absorbed and unabsorbed QSOs we have used, then in Section 3 we present the submm photometry results on those two samples. The results of submm imaging around some of the X-ray absorbed QSOs are shown in Section 4, and we discuss the possible nature of the submm sources appearing around those QSOs. The available *XMM-Newton* observations are briefly summarized in Section 5 (for a full account see Page et al. 2006, this volume). Finally, the ensemble of results are discussed and interpreted in the framework of a hierarchical evolution of spheroids in Section 6.

2. SAMPLE SELECTION

We have assembled two similarly sized samples of broad line QSOs, with similar redshift distributions ($1 < z < 3$) and soft X-ray luminosities ($\log(L_{\rm X,soft} = \log(L^*_{\rm X} \pm 0.7$), where the bulk of the QSO luminosity density was produced (Page et al. 1997, Miyaji et al. 2001). Most of the objects in both samples are expected to be radio quiet, since the ratio between radio quiet and radio loud objects in the above intervals is 15 to 1 (Ciliegi et al. 1995).

The key difference between the two samples is that one of them is composed of 20 QSOs without absorption in their X-ray spectra, as are most soft X-ray selected AGN (Mateos et al. 2005). The 19 QSOs in the other sample show Compton-thin absorption in their X-ray spectra (Page et al. 2001a). This is in itself rather surprising, since, within unified models for AGN, the material obscuring the central regions is located in a geometrically and optically thick torus, which should block both the X-ray and broad line emitting regions. We will propose a possible way out of this contradiction in Section 5.

Again within the Unified model for AGN, the difference between both samples should be due simply to geometry, hence it would be expected that isotropic properties (such us the submm emission from heated dust) is identical between both samples.

3. SUBMILLIMETER PHOTOMETRY

We have performed SCUBA photometry at 450 and 850 μm (Page et al. 2001b, Page et al. 2004, Stevens et al. 2005) of both samples of objects, finding that 8 out of 19 absorbed QSO were detected at 3σ in 850 μm (all at $z > 1.5$), while only 1 of the 20 unabsorbed QSOs was detected (Fig. 1). This difference is significant at $> 3\sigma$, increasing to $> 4\sigma$ if only $z > 1.5$ sources are considered. This difference is completely at odds with the unified models. There must be some physical relationship between the absorbed nature of some of the QSOs and their submm emission.

We have calculated the FIR luminosity of these objects from their observed submm flux using the SED of Mrk 231 (a nearby X-ray abs. Ultra Luminous Infrared Galaxy -ULIRG-) as a template. With this recipe, all the detected absorbed QSO are ULIRG. But, what is the origin of this FIR emission? Could it be due to dust heated by the QSO?

To answer this question, we have also estimated the bolometric luminosities of the QSO, scaling from their soft X-ray luminosities using the QSO template from Elvis et al. (1994). In four of our submm detected absorbed QSO the FIR emission is larger than their bolometric QSO luminosities, in three other objects it is greater than fifty percent, and in the last one it is around thirty percent (Stevens et al. 2005). We conclude then that most of their FIR emission must come form dust heated by starburst

Their detection as strong X-ray and FIR emitters shows that these objects are building up simultaneously their stellar populations and their central SMBH. The deduced star formation rate (Kennicut 1998) is higher than 1000 $M_\odot$/y, sufficient to build a substantial fraction of a galaxy spheroid in only a few 100 Myr.

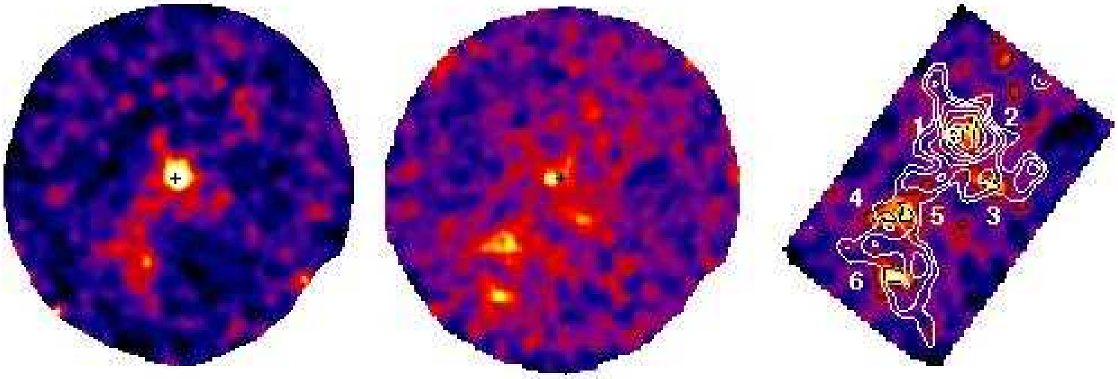

Figure 2. Submillimeter imaging of the field around RX J094144.51+385434.8. The left-hand panel shows the SCUBA 850 μm image (diameter ∼150", resolution 14.8"). The middle panel shows the corresponding 450 μm image (diameter ∼120", resolution 8.5"). The right-hand panel shows a signal-to-noise image (1.5'×1.0') at 450 μm (greyscale with black contours at 2, 3, 4 and 5σ) overlayed with the 850 μm signal-to-noise contours at 2, 3, 4, 5, 6, 7 and 8σ. The optical position of the QSO is marked with a cross on the left-hand and middle panels.

In addition, we have only detected absorbed QSO as submm sources at $z > 1.5$, it is then interesting to check whether they also show significantly higher star formation rates at higher redshifts as radiogalaxies (Archibald et al. 2001). In the full sample of absorbed QSOs both $L_{\rm FIR}$ and $L_{\rm X}$ are correlated with z, and between them. If we pick up a subsample of absorbed QSO with $44.5 \leq \log L_{\rm X}({\rm erg/s}) \leq 45$, over which their $\log L_{\rm X}$ is not correlated to z (Stevens et al. 2005), $L_{\rm FIR}$ is still correlated with z, but not with $L_{\rm X}$. Therefore, X-ray absorbed QSOs had higher FIR luminosities (and hence star formation rates) in the past.

4. THE ENVIRONMENTS OF THE ABSORBED QSOS

As part of an ongoing programme to obtain SCUBA submm imaging in regions (∼2 arcmin diameter) around our submm-brighter absorbed QSO, we have found strong overdensities of submm sources around two of them: RX J094144.41+385434.8 (Stevens et al. 2004) and RX J121803.82+470854.6 (Stevens et al., in preparation).

The sky density of submm sources around the first one is 1.4 ± 0.6 arcmin^{-2}, an order of magnitude higher than in empty fields (Smail et al. 2002), with a probability of a chance superposition of field objects of $\sim 10^{-7}$. This provides very strong evidence that the companion galaxies lie at the same redshift and in the same structure as the QSO. If this were the case, the chain of six submm sources detected in this field would form a ∼400 kpc long filament. Each one of them would be itself an ULIRG producing stars at a rate sufficient to build a massive spheroid in less than a Gyr. Some of these sources present complex submm morphologies, indicative of major mergers. Very few of them are detected in X-rays, so they must be heavily obscured if they contain AGN.

We have obtained multiwavelength imaging around those two (and other) QSOs, including R, i, J, K and *Spitzer* 4.5 μm, 8 μm and 24 μm images. We are still analysing them to get photometric redshifts for the detected optical/IR sources, and hence decide which are the most likely counterparts to the submm sources, and to look for structure at the redshift of the central QSO (Ebrero et al. 2006, in preparation). The galaxies closer to the submm sources are mostly faint EROs with $K \geq 19$ and $R > 24$ (Stevens et al. 2004). In Fig. 3, we show K and 450 μm SNR contours over *Spitzer* 4.5 and 8 μ images, showing that some of the submm sources have *Spitzer* but no K-band counterparts. This probably means that the corresponding galaxies are highly dusty and heavily obscured, contain buried AGN, or both.

5. *XMM-NEWTON* OBSERVATIONS

We have so far *XMM-Newton* AO-4 data for three of our absorbed QSOs. Preliminary analysis of the coadded MOS+pn spectra (Page et al. 2006, this volume) show that they can be fit by flat simple powerlaws ($\Gamma \sim 1.4$), much flatter than the "canonical" $\Gamma = 2$ AGN slope (Mateos et al. 2005). Cold absorption of a canonical spectrum is rejected for two of them, while ionized absorbers with that slope, $\log \xi \sim 2$ and column densities $\sim 10^{22.5} - 10^{23.5}$ cm^{-2} are acceptable fits. With these conditions, the absorbers probably originate within the AGN.

Dust (responsible for the optical and UV extinction) would not survive in such ionized X-ray absorbers, solving thus the apparent contradiction between the presence

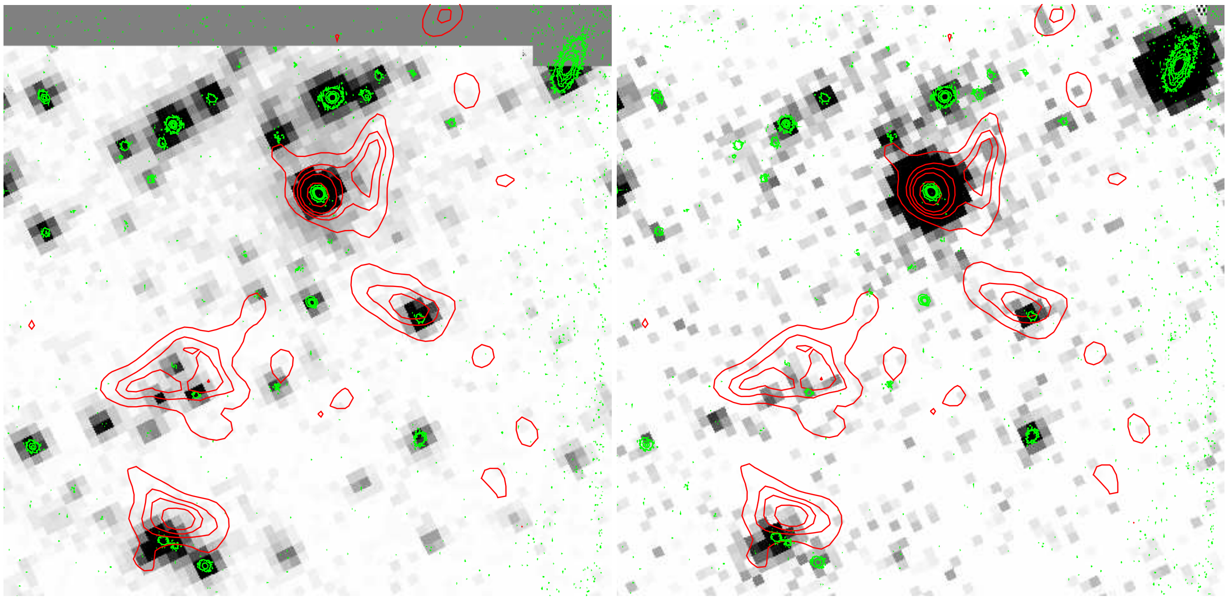

Figure 3. **Left**: *Spitzer 4.5 μm image ($\sim (1')^2$) with K (green -light in greyscale-) and 450 μm (red -dark-, 2, 3, 4, 5σ) contours.* **Right**: *Spitzer 8 μm image (scale and contours are the same as in the left panel).*

of broad optical/UV lines and strong X-ray absorption within the unified model for AGN (see Page et al. 2006 for a longer discussion).

6. DISCUSSION AND CONCLUSIONS

We have found that X-ray absorbed QSO are strong FIR emitters, while unabsorbed QSOs are not. We have shown that the FIR emission must come from star formation, implying that unabsorbed QSO hosts are already formed, while absorbed QSOs are still actively forming stars. At the same time, the BH masses deduced from the X-ray luminosities of the absorbed QSOs are $> 10^8$ M$_\odot$, showing that their BH are already relatively mature. From the relative densities of absorbed and unabsorbed QSOs we infer (Page et al. 2004) that the duration of the absorbed phase is ~15% of the duration of the unabsorbed phase. Finally, there is merger-induced activity in (and around) some of our absorbed QSOs, which seem to inhabit high-density regions of the Universe.

From the above, plus the fact that star formation in absorbed QSOs was stronger in the past, we conclude that the absorbed phase must precede the unabsorbed phase, and star formation and mergers must have something to do with it.

This can be interpreted as an evolutionary sequence within a joint spheroid/QSO evolution in a hierarchical clustering scenario (see Fig. 4, Granato et al. 2004, Silk & Rees 1998, Fabian 1999, Di Matteo et al. 2005): the more massive dark matter halos collapse earlier, giving rise to collisions and mergers, which channel material to the center, triggering star formation and feeding the central BH. This material obscures strongly the optical, UV and X-ray emission, while the heated dust emits FIR radiation which escapes unimpeded.

As star formation progresses, the FIR emission increases, reaching ULIRG luminosities, at which stage these sources could be the bulk of the submm galaxy population discovered by SCUBA (Smail et al. 1997). At the same time the BH keeps growing, reaching Seyfert-like X-ray luminosities (like the objects detected by Alexander et al. 2005, and discussed by Borys et al. 2005), with signatures of buried AGN in their optical spectra (Chapman et al. 2003).

Still forming stars vigorously, the central BH of these objects will eventually reach QSO luminosities. The QSO radiation and star formation processes start sweeping out circumnuclear material, reducing gradually the absorption and the rate of star formation, and giving rise to properties very similar to our absorbed QSOs, or BAL QSOs in slightly later stages (Fabian 1999).

Eventually, the bulk of the circumnuclear material is swept away, leaving a fully grown naked QSO “living off the rents”, with a passively evolving stellar population, like the “standard” unabsorbed QSOs. Eventually the QSO exhausts its fuel reservoir, leaving a dormant SBMH in the center of a “normal” galaxy, like the ones seen in the local Universe.

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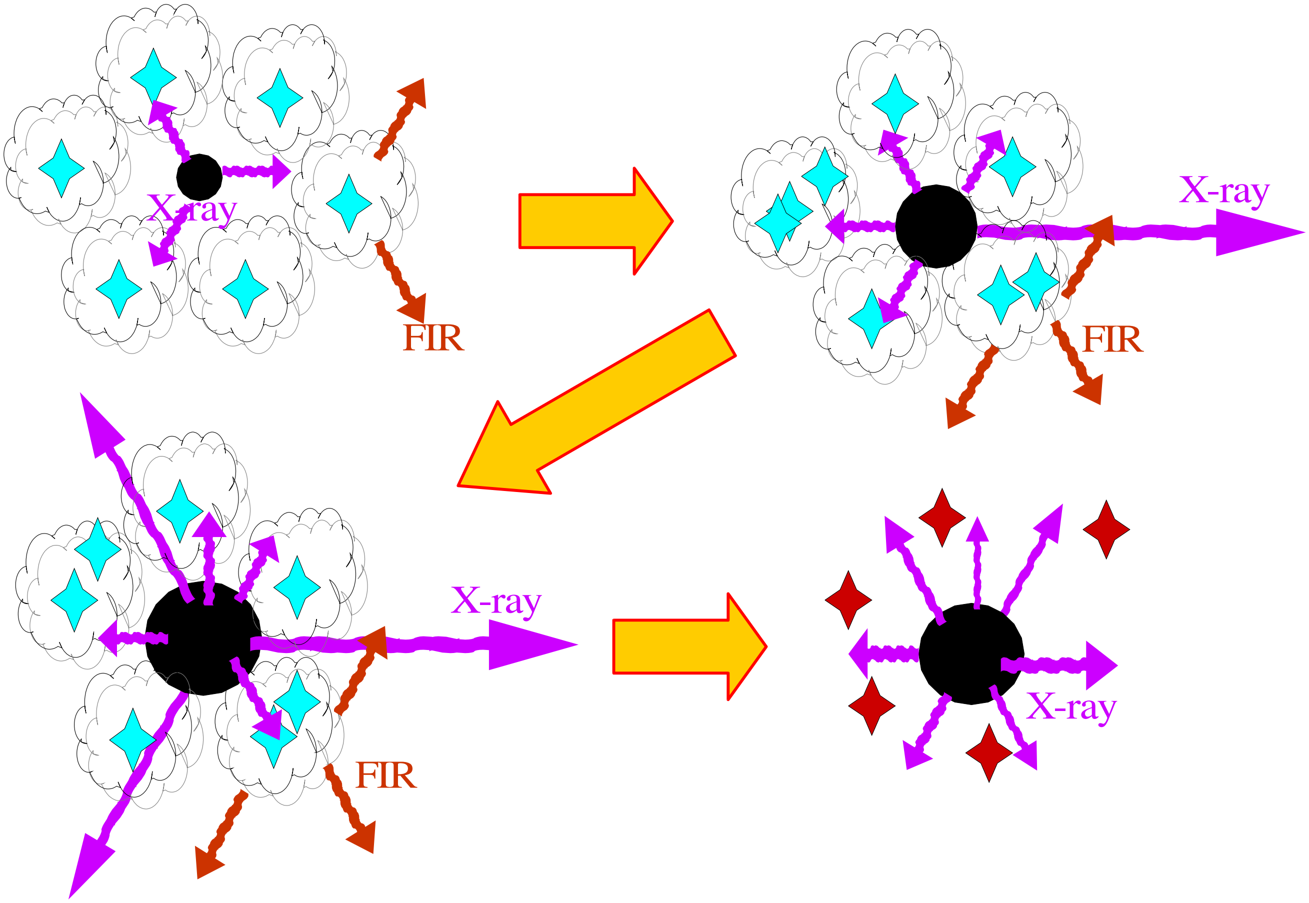

Figure 4. Joint spheroid/QSO evolutionary sequence: **Top-left***: Heavily obscured growth of BH, with strong star formation emitting in FIR.* **Top-right***: Star formation reaches ULIRG luminosities, while SMBH reaches Sy-like luminosities, still heavily obscured.* **Bottom-left***: Obscured QSO-like luminosities of SMBH and strong star formation (our absorbed QSO).* **Bottom-right***: Most of the circumnuclear material is swept away, leaving a naked QSO with passively evolving spheroid (standard unabsorbed QSO), which eventually becomes a "normal" galaxy with a SMBH in its centre.*