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X-ray and submillimetre observations of star-forming QSOs in the epoch of galaxy formation

M.J. Page[1], F.J. Carrera[2], J.A. Stevens[3], M. Symeonidis[1], J.D.Vieira[4], and HerMES[5]

[1] Mullard Space Science Laboratory, Holmbury St. Mary, Dorking, Surrey RH5 6NT, UK
e-mail: m.page@ucl.ac.uk
[2] Instituto de Física de Cantabria, Avenida de los Castros, 39005 Santander, Spain
[3] Centre for Astrophysics Research, University of Hertfordshire, College Lane, Hatfield AL10 9AB, UK
[4] California Institute of Technology, 1200 E. California Blvd, Passadena, CA 91125, USA
[5] http://hermes.sussex.ac.uk

Abstract. X-rays are the most efficient means to identify distant AGN, while submillimetre observations expose star formation in their hosts. Prior to *Herschel*, X-ray surveys combined with ground-based submillimetre observations identified a subset of luminous, X-ray absorbed QSOs, as being embedded in powerful star-forming galaxies. X-ray spectra from *XMM-Newton* provide strong evidence that the X-ray absorbers in these objects are highly-ionized winds, generated by the AGN rather than originating in the interstellar medium of the host galaxy. New results obtained from the *Herschel* HerMES observations of the *Chandra* deep fields, which pair the deepest submillimetre images with the deepest X-ray surveys allow us to extend the study of submillimetre emission from distant AGN hosts to objects of much lower X-ray luminosity. Remarkably, while submillimetre emission is rare in the hosts of AGN with $L_X > 10^{44}$ ergs s^{-1}, it is quite common in $1 < z < 3$ AGN with L_X between 10^{43} and 10^{44}. We interpret the relative paucity of star formation in powerful AGN hosts, and the presence of substantial ionized winds in the few powerful, star-forming QSOs as evidence that luminous AGN terminated the star formation in their hosts via powerful winds.

Key words. X-rays: galaxies – galaxies: active – galaxies: evolution – galaxies: formation

1. Introduction

The prevalence of black holes in present day galaxy bulges, and the proportionality between black hole and spheroid mass (Merritt & Ferrarese 2001) implies that the formation of the two components are intimately linked. One way to probe star formation in distant QSOs is to observe them at submillimetre wavelengths, and so measure the amount of radiation from young stars which is absorbed and re-emitted by dust in the far infrared. With this in mind, we observed matched

Send offprint requests to: M. J. Page

samples of X-ray absorbed and unabsorbed QSOs at 850μm with SCUBA at the James Clerk Maxwell Telescope. These observations revealed a remarkable dichotomy in the submillimetre properties of these two groups of sources: almost all of the X-ray absorbed QSOs at $z > 1.5$ are ultraluminous infrared galaxies, while the X-ray unabsorbed QSOs are not (Page et al. 2001, 2004). This suggests that the two types are linked by an evolutionary sequence, whereby the QSO emerges at the end of the main star-forming phase of a massive galaxy (Page et al. 2004; Stevens et al. 2005; Carrera et al. 2006).

However, the nature of the X-ray absorption required further examination. These objects are characterised by hard, absorbed X-ray spectra, and assuming that this is due to photoelectric absorption from cold material with solar abundances, their column densities are $\sim 10^{22}$ cm^{-2}. On the other hand, they have optical/UV spectra which are typical for QSOs, with broad emission lines and blue continua. For a Galactic gas/dust ratio, the rest-frame ultraviolet spectra would be heavily attenuated by such large columns of material, so the absorbers appear to contain very little dust. The X-ray absorption could be due to gas located within the AGN structure, or from more distant material in the host galaxy. If the absorption were associated with the obscuring dusty torus invoked in unification schemes (Antonucci 1993) we would expect significant dust attenuation, while the detection of the dust continuum at long wavelengths implies that the interstellar media of the host galaxies are also dust-rich. In order to investigate the X-ray absorption, we therefore obtained deep (50–100ks) *XMM-Newton* observations of five submillimetre-bright, X-ray absorbed QSOs from our sample of hard-spectrum *Rosat* sources (Page, Mittaz & Carrera 2001).

2. XMM-Newton spectra

The *XMM-Newton* spectra for three of our star-forming QSOs are shown in Fig. 1. The spectra were compared to two models: a power-law continuum of arbitrary photon index with a neutral absorber, and a powerlaw continuum

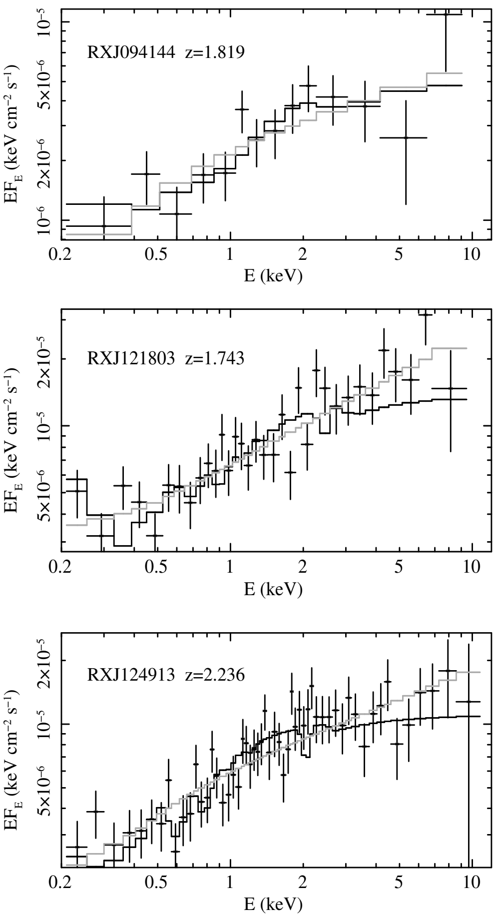

Fig. 1. EPIC spectra of 3 star-forming, X-ray absorbed QSOs, from Page et al. (2011). The grey stepped lines correspond to neutral-absorber models, and the black stepped lines to ionized-absorber models.

with photon index fixed at $\Gamma = 1.9$, typical for X-ray selected QSOs (e.g. Mateos et al. 2005; Page et al. 2006), and an ionized absorber. In the first model, the photon index of the continuum and the column density of the absorber are free parameters, while in the second model the ionization parameter and column density of the absorber are free parameters. Both models can fit the data acceptably in terms of χ^2, but in the first model the derived continuum photon indices and X-ray to optical flux ratios stray beyond the normal range for QSOs, leading to a rather contrived scenario in which the QSOs would be both absorbed and intrinsically unusual in spectral shape. In contrast, the second model implies intrinsically-normal QSOs shining through ionized absorbers with plausible ionization parameters (log ξ between 2 and 3), and column densities (N_H of $10^{22.5}$ – $10^{23.5}$ cm^{-2}). We favour the second model because it provides the simplest, most self-consistent explanation of the observed properties; for full details see Page et al. (2011).

At the ionisation parameters and column densities implied by our model fits, the absorbers are likely to originate in the AGN themselves, rather than in the host galaxies. This solution is attractive, because it is compatible with the lack of optical extinction in these objects: if the absorber is driven as a wind, either from the accretion disc or from evaporation of the inner edge of the molecular torus, then dust will be sublimated before (or as) it enters the flow.

With the hypothesis of an outflowing, ionised wind in mind, we now turn to the optical spectra of our five QSOs, which correspond to the UV in the restframe of the QSOs. It is notable that all five objects show significant absorption lines of C IV, in most cases blueshifted with respect to the systemic redshifts determined from the emission lines. Noting that the ionised X-ray absorbers in nearby Seyferts are normally accompanied by absorption lines in the UV, and assuming that the UV absorption lines in our QSOs are associated with the X-ray absorbers, we can use the UV absorption line velocities to investigate the likely kinematics and energetics of the X-ray absorbers. We also assume that the absorbers have similar filling factors (~ 0.01) to ionised absorbers with comparable ionisation parameters in well studied, nearby AGN (Ashton et al. 2006). We find that for a typical X-ray absorbed QSO, with a wind outflow velocity of 8000 km s^{-1}, the mass outflow rate in the wind is about 10 times the accretion rate, and the kinetic power of the wind is equivalent to $\sim 4\%$ of the radiative luminosity, albeit with large uncertainty.

3. Probing lower X-ray luminosities with Herschel

The remarkable speed with which *Herschel*'s SPIRE camera can image the sky at 250, 350 and 500 μm permits much larger and more sensitive surveys of the star formation in distant AGN host galaxies than were possible with ground based submillimetre telescopes, and in combination with the extremely deep integrations carried out with *Chandra* in X-rays allow us to probe star formation in the host galaxies of AGN with X-ray luminosities well below 10^{44} ergs s^{-1}.

Fig. 2 shows the redshifts and 2-8 keV luminsities of X-ray selected AGN in the *Chandra* Deep Field North, with the objects detected in the 250 μm *Herschel* SPIRE image of the same region shown as bold circles. There is a remarkable difference between the detection rates of $1 < z < 3$ AGN with luminosities above and below 10^{44} ergs s^{-1}. None of the $L_X > 10^{44}$ AGN are detected in the submillimetre image, in keeping with our findings with SCUBA that, apart from X-ray absorbed QSOs, luminous X-ray selected AGN are rarely powerful submillimetre sources. However a significant fraction of AGN with $10^{43} < L_X < 10^{44}$ (25% in this field) are detected in the 250 μm image, and examination of their SEDs indicates that the submillimetre emission originates from powerful starbursts in their host galaxies (Page et al. 2012). At these lower X-ray luminosities, AGN are frequently hosted by ultraluminous starburst galaxies but at higher X-ray luminosities such prodigious star formation is rare, except in X-ray absorbed QSOs.

4. Implications for AGN and galaxy evolution

The scarcity of strong submillimetre detections of QSOs with $L_X > 10^{44}$ ergs s^{-1}, in studies with both *Herschel* and SCUBA, compared to less luminous AGN, suggests that the star formation has been suppressed in the host galaxies of AGN when they are at the peak of their accretion power. The presence of prodigious star formation in the 5–10% of $L_X >$

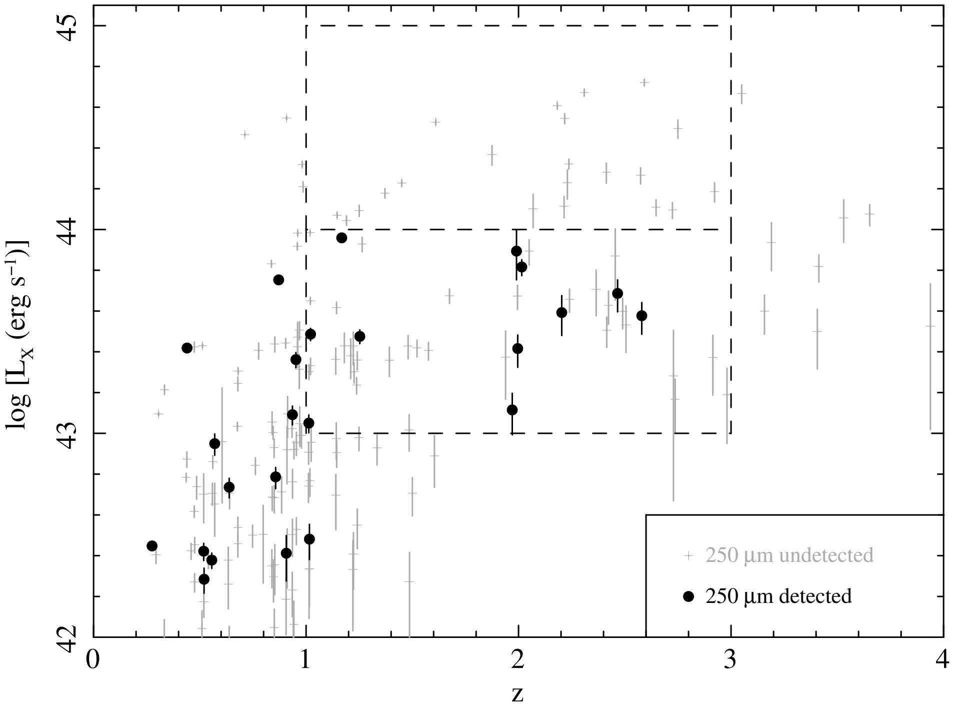

Fig. 2. Redshifts and X-ray luminosities for AGN in the *Chandra* Deep Field North. Objects detected at 250 μm with *Herschel* SPIRE are indicated as bold circles.

10^{44} QSOs which are X-ray absorbed suggests that these objects are caught during a short-lived transitional phase, between the ultraluminous, submillimetre starburst and the naked QSO which shines brightly until its fuel is consumed. A number of theoretical models predict a very similar evolutionary pattern. In many of these models, the QSO terminates the star formation in the host galaxy by driving a powerful wind (e.g. Silk & Rees 1998; Di Matteo Springel & Hernquist 2005). The EPIC spectra of our X-ray absorbed QSOs suggest that their absorbers are ionised winds driven by the AGN, and therefore that the transition between buried AGN and naked QSO could indeed be mediated by a radiatively driven wind from the AGN, as predicted by these models.

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