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The X-ray–Infrared/Submillimetre Connection and the Legacy Era of Cosmology

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We review some recent results on the identification and characterisation of Active Galactic Nuclei (AGN) obtained by cross correlating X-ray surveys with infrared and submillimetre surveys. We also look towards the scientific gains that could be achieved from an *XMM-Newton* survey of the $\approx$ 20–50 deg^2 legacy fields that are being observed at $\approx$ 1–850 μm.

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1 Introduction

Deep infrared (IR) and submillimetre (submm) surveys are providing a sensitive view of the Universe at $\approx$ 3–850 μm (e.g., Coppin et al. 2006; Dole et al. 2006; Frayer et al. 2006), revealing large numbers of dust-obscured starburst galaxies and Active Galactic Nuclei (AGN). These surveys have found that luminous IR galaxies strongly evolve out to $z \approx$ 1–2, implying that a large (possibly dominant) fraction of the growth of galaxies occurred at high redshift in an IR-bright phase. Detailed studies have, indeed, suggested that at least half of all newly born stars are formed in LIRGs ($L_{\rm IR} \approx 10^{11}$–$10^{12}$ $L_\odot$) hosted in moderate-mass galaxies at $z < 1.5$ (e.g., Le Floc'h et al. 2005; Perez-Gonzalez et al. 2005), and that distant ULIRGs ($L_{\rm IR} > 10^{12}$ $L_\odot$) represent a key phase in the formation of the spheroids of today's massive galaxies (e.g., Chapman et al. 2005; Swinbank et al. 2006).

Although providing a detailed insight into the formation and evolution of the majority of the stellar population, a large uncertainty in the interpretation of these studies is the contribution (or "contamination") from IR-bright AGNs, which could be significant. For example, the best estimates on the total amount of star formation overproduce the stellar-mass density by a factor of ≈ 2 (e.g., Chary & Elbaz 2001; Hopkins & Beacom 2006), a discrepancy which would be neatly explained by a large population of hitherto unidentified obscured AGNs. Furthermore, given the tight relationship between the mass of galaxy spheroids and their central black holes (e.g., Magorrian et al. 1998; Tremaine et al. 2002), it might also be expected that any major star-formation phase co-incides with periods of AGN activity, during which the black hole is grown in tandem. Although the global evolution of star formation and AGN activity is comparatively well constrained (e.g., Madau et al. 1996; Barger et al. 2005; Hasinger et al. 2005; Hopkins & Beacom 2006), the details of how galaxies and their black holes grew (e.g., as a function of environment, cosmic epoch, and mass) are still largely unknown.

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Arguably, the most direct indication of AGN activity is the detection of luminous hard X-ray emission (i.e., >2 keV). Hard X-ray emission appears to be a universal property of AGNs, giving a direct "window" on the emission regions closest to the black hole (e.g., Mushotzky, Done, & Pounds 1993), and it can provide a secure AGN identification in sources where the optical signatures and counterparts are weak or even non existent (e.g., Alexander et al. 2001a; Comastri et al. 2002). Hard X-ray emission is also relatively insensitive to obscuration (at least for sources that are Compton thin; i.e., $N_{\rm H} < 1.5 \times 10^{24}$ cm^{-2}) and any hard X-ray emission from star formation in the host galaxy is often insignificant when compared to that produced by the AGN. Importantly, the X-ray emission from AGNs provides a direct measurement of the primary power of the AGN, crucial information when estimating mass accretion rates and the relative bolometric contributions from AGN and star-formation activity (e.g., Alexander et al. 2005a,b). The IR/submm band, by comparison, often probes the dominant component of the bolometric output of luminous galaxies/AGNs but since it measures the dust-reprocessed emission it provides ambiguous information on the primary contributions from AGN activity and star formation. A notable exception to this is the identification of Compton-thick AGNs, where the observed X-ray emission is often very faint and dominated by reflected/scattered components. For these most heavily obscured objects, the IR/submm band can provide indirect insight into the energetics of the AGN activity.

Here we review some recent results obtained from the cross correlation of X-ray and IR/submm surveys. We also look towards the scientific gains that could be achieved from an *XMM-Newton* survey of the $\approx$ 20–50 deg^2 legacy fields

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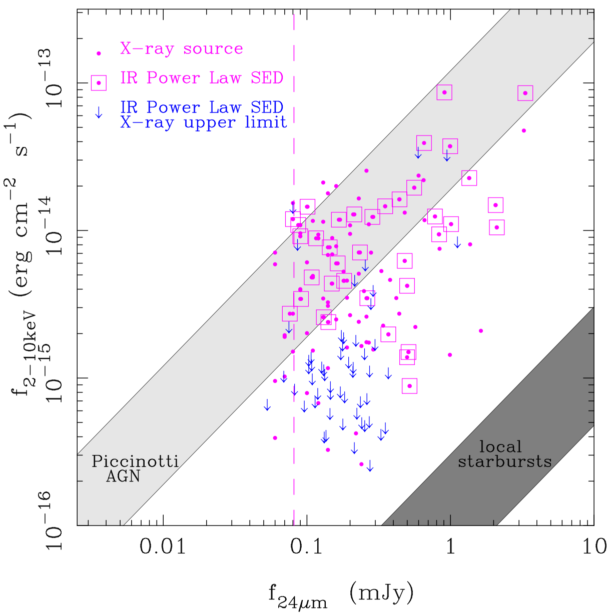

Fig. 1 Hard X-ray flux versus 24 μm flux density for X-ray identified (filled dots) and IR-identified AGNs (open squares and arrows) in the *Chandra* Deep Field-South. The light shaded region indicates where (comparatively unobscured) AGNs and starbursts with flux ratios consistent with local objects would lie. Taken from Alonso-Herrero et al. (2006).

being observed at 1–850 μm (VISTA, UKIDSS, *Spitzer*, *Herschel*, SCUBA2).

2 The Advances Made by *XMM-Newton* and *Chandra*

Early studies on the connection between X-ray and IR/submm sources focus on nearby objects, or rare, luminous AGNs (e.g., Barcons et al. 1995; Alexander et al. 2001b). The orders of magnitude increase in sensitivity that *XMM-Newton* and *Chandra* have provided over previous X-ray observatories, allied to the sensitivity gains made by *Spitzer* and premier submm instruments (e.g., SCUBA and MAMBO), can now yield insight into the role of typical AGNs in IR/submm galaxies out to high redshift.

The current X-ray–IR cross-correlation studies have typically focused on characterising the IR Spectral Energy Distributions (SEDs) of X-ray and IR selected AGNs. As known since IRAS, about half of the nearby AGN population are identifiable as AGN from their IR SEDs while the other half have IR properties more consistent with those expected from star formation (see Fig. 3 of Alexander 2001). A good example of the latter is NGC 6240, a nearby powerful AGN hosted in a starburst galaxy, that only clearly reveals the signatures of luminous AGN activity at hard X-ray energies (e.g., Vignati et al. 1999). A similar dichotomy is being found for more distant objects identified in *Spitzer* surveys. For example, using only moderately deep X-ray observations, up-to $\approx$ 30% of the X-ray identified AGN have starburst-like IR SEDs (e.g., Franceschini et al. 2005; Polletta et al. 2007); the fraction approaches $\approx$ 50% with deeper X-ray surveys (e.g., Alonso-Herrero et al. 2004; Alexander 2006; see Fig. 1). Conversely, selecting IR galaxies with AGN-like SEDs, it has also been possible to identify heavily obscured (potentially Compton thick) AGNs that are not detected at X-ray energies (e.g., Alonso-Herrero et al. 2006; Polletta et al. 2006; Donley et al. 2007). The latest results suggest that Compton-thick AGN in the distant Universe could be wide spread, accounting for a large fraction of the growth of black holes (e.g., Daddi et al. 2007; Fiore et al. 2007). It is from a combination of X-ray and IR observations that Compton-thick AGN can be effectively identified; radio and X-ray observations can also provide a sensitive probe of Compton-thick AGN activity (e.g., Donley et al. 2005; Martínez-Sansigre et al. 2007) and will become key resources with LOFAR and the SKA.

Cross correlation studies of X-ray and submm surveys have shown that X-ray identified AGN are faint and, typically, only detected in deep X-ray surveys (see Fig. 1 of Alexander et al. 2003). There are two major reasons for this (1) the flat selection function of submm blank-field surveys means that the majority of submm-emitting galaxies (SMGs) are detected at high redshift ($z \approx 2$; e.g., Smail et al. 2002; Chapman et al. 2005), making them faint at most other wavelengths, and (2) detailed X-ray spectral analyses have indicated that the majority of the AGNs are heavily obscured and only moderately luminous at X-ray energies (e.g., Alexander et al. 2005a). Since SMGs are amongst the most bolometrically luminous galaxies in the Universe, the relatively weak X-ray emission implies that the AGN activity is unlikely to dominate the global energetics (e.g., Alexander et al. 2005a). Indeed, mid-IR spectroscopy of SMGs has shown that the dominant power source of SMGs appears to be star formation (e.g., Valiante et al. 2007; Menéndez-Delmestre et al. 2007; Pope et al. 2007). However, the large fraction of SMGs that host AGN activity ($\approx$ 28–50%) indicates that their black holes are growing almost continuously throughout periods of intense star formation (e.g., Alexander et al. 2005b). Careful assessment of the black-hole and host-galaxy masses of SMGs indicates that their black holes are smaller than those expected for comparably massive galaxies in the local Universe (e.g., Borys et al. 2005; Alexander et al. 2007), indicating that they must undergo an intense black-hole growth phase before the present day. Observational evidence suggests that this rapid black-hole growth phase is associated with optically luminous quasar activity (e.g., Page et al. 2004; Stevens et al. 2005; Alexander et al. 2007), in general agreement with predictions from simulations of SMG-like systems (e.g., Granato et al. 2006; Chakrabarti et al. 2007).

The combination of X-ray and IR/submm surveys have furthered our understanding of AGNs in the distant Universe and increased the global "census" of AGN activity. However, the current results on the relative growth of galaxies and their black holes have mostly focused on the lu-

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minous objects identified in submm surveys or luminous quasars; the statistics of the former are currently limited. There has also been little research on what causes distant black holes to grow (e.g., environment, galactic/halo mass and galactic morphology). Since only a small fraction of galaxies undergo AGN activity at any given time, to fully explore this topic over a wide range of environments requires sensitive multi-wavelength coverage over large areas of the sky.

3 The Legacy Era of Cosmology

Over the last few years, a large amount of astronomical resources have been committed to compiling deep multi-wavelength data over large areas of the sky. These extensive datasets provide the potential to trace the growth of galaxies, their black holes, and the large-scale structure that they reside in, across a large fraction of cosmic time. The large investments of time required to achieve these goals have led to the datasets becoming publicly available on short timescale to maximise their scientific potential.

In terms of observational cosmology, the *Spitzer*-SWIRE survey probes a key region of sensitivity–solid angle parameter space at $\approx$ 3–160 μm (Lonsdale et al. 2003, 2004). Covering $\approx$ 50 deg^2 over 6 fields, this survey traces the growth of galaxies out to $z \approx 1$ across a broad range of environments, from galaxy voids to galaxy superclusters (linear scales of $\approx$ 50–100 Mpc at $z \approx 1$). The multi-wavelength coverage of these fields is rapidly growing, and upcoming surveys with *Herschel* and SCUBA2 extend this coverage out to $\approx$ 850 μm, while surveys with VISTA and UKIDSS cover the shorter wavelength range at $\approx$ 1–2.5 μm.[1] Over $\approx$ 1–850 μm, the total investment of time in these fields is already of order $\approx$ 20–30 Ms. This investment of time does not include large amounts of additional radio and optical imaging and spectroscopic observations already undertaken and planned for the additional exploitation of these fields. In Fig. 2 we show the predicted IR sensitivity for some of these surveys; LIRGs are detectable out to $z \approx$ 0.5–2 and ULIRGs will be identified out to higher redshifts. However, a major wavelength component missing from this large legacy survey is complete and sensitive X-ray coverage.

A moderately deep *XMM-Newton* survey of the $\approx$ 20 deg^2 of the SWIRE fields, where there is the maximum overlap between the different multi-wavelength surveys, would provide the most direct constraints on the energetics of AGN activity and black-hole growth in these fields. A key scientific area that such a survey would provide is constraining the environments and conditions in the distant Universe that lead to black-hole growth. For example, the exploration of IR-selected galaxies at $z \approx 1$ has indicated that galaxies in dense regions are growing more rapidly than those in underdense regions, in stark contrast to that found in the local Universe (e.g., Elbaz et al. 2007). Only a large-area sensitive X-ray survey would detect sufficient numbers of AGNs over a wide enough range of environments to explore the effect of environment on the growth of black holes. For example, an *XMM-Newton* survey of these fields with $\approx$ 30–60 ks pointings would achieve a 2–10 keV luminosity of $\approx 10^{43}$–10^{44} erg s^{-1} at $z \approx$ 1–3, sufficient to identify moderately luminous Seyfert galaxies out to high redshift. This survey would detect $\approx$ 10,000–20,000 AGNs ($\approx$ 10% will lie at $z > 3$ and $\approx$ 10% will be obscured quasars with $L_{\rm X} > 10^{44}$ erg $^{-1}$) and $\approx$ 500 galaxy clusters (a few with $\approx 10^{15}\ M_\odot$), providing sufficient statistics to investigate AGN activity as a function of many different physical properties. The large-area coverage would also allow, for example, constraints on the clustering of AGNs as a function of different parameter space, the detection of rare luminous objects not found in smaller fields (e.g., luminous obscured submm-emitting quasars; $z > 1$ galaxy clusters), the identification of luminous Compton-thick AGNs, and will place detailed constraints on the evolution of AGN activity in galaxy clusters out to $z \approx 1$ (see Geach et al. 2006 for one of the first studies of the evolution of star formation in distant galaxy clusters).

An *XMM-Newton* survey of the parameters given above would require of order $\approx$ 10–20 Ms. This is a large investment of time, however, the complementary multi-wavelength data necessary to perform detailed analyses of the detected sources would already be in hand, providing excellent value-for-money when compared to the arduous task that would be required to acquire similarly sensitive multi-wavelength data of fields with just X-ray coverage. The wide distribution of the six fields across the sky would also allow for convenient scheduling of the *XMM-Newton* observations, minimising the impact on other scheduled X-ray observations. A wide-area *XMM-Newton* survey of key IR/submm legacy fields would provide a major astronomical resource for decades to come, achieving sensitivity limits at least an order of magnitude deeper than planned large-area hard X-ray surveys (e.g., *e-ROSITA*).

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[1] See http://astronomy.sussex.ac.uk/~sjo/Hermes/ for more details on these surveys

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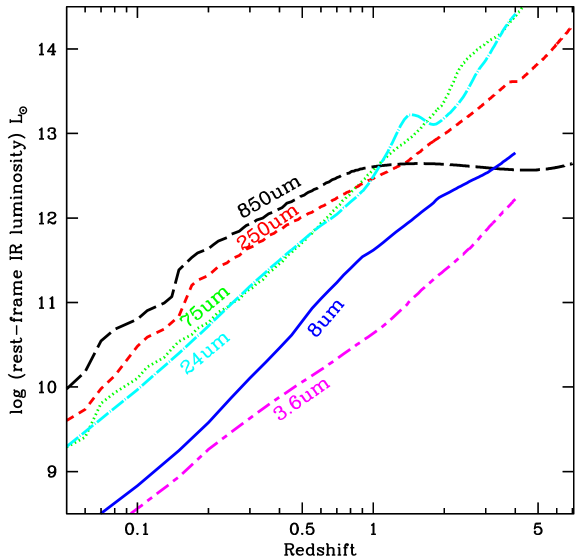

Fig. 2 Predicted luminosity at 8–1000 μm versus redshift for some of the surveys being performed in the SWIRE legacy fields; the luminosities are calculated using the Chary & Elbaz (2001) SEDs. The different curves represent different selection wavebands (as annotated). Tracks used in figure produced by D. Elbaz.

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