The X-ray/submillimetre Link

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Abstract. It is widely believed that most of the cosmic X-ray background (XRB) is produced by a vast, hitherto undetected population of obscured AGN. Deep X-ray surveys with Chandra and XMM will soon test this hypothesis. Similarly, recent sub-mm surveys with SCUBA have revealed an analogous population of exceptionally luminous, dust-enshrouded star-forming galaxies at high redshift. There is now growing evidence for an intimate link between these obscured populations. There are currently large uncertainties in the models, but several independent arguments lead to the conclusion that a significant fraction of the SCUBA sources (10 − 30%) will contain quasars. Recent observational studies of SCUBA survey sources appear to confirm these predictions, although the relative roles of AGN and star-forming activity in heating the dust are unclear. Forthcoming surveys combining X-ray and sub-mm observations will provide a very powerful tool for disentangling these processes.

1 Obscured AGN and the X-ray background

The origin of the cosmic X-ray background (XRB) has been a puzzle for over 35 years, but now there is strong evidence that this will be explained by a large population of absorbed AGN. If these are to explain the bump in the XRB spectrum at 30keV, however, the total energy output of this population must exceed that of broad-line AGN by at least a factor of ∼ 5, with wide ranging implications [17]. This hidden population could also explain the apparent discrepancy between the black hole densities predicted by ordinary QSOs and recent observations of local galaxy bulges [13], [3].

Deep X-ray surveys with Chandra and XMM will soon test this obscured AGN hypothesis, although existing surveys with ROSAT, ASCA and BeppoSAX have already revealed what could be the ‘tip of the iceberg’ of this population. Several unambiguous cases of obscured QSOs have been detected (e.g. [3], [7], [2], [9], [2]) while at the faintest X-ray fluxes there is growing evidence for a large population of X-ray luminous emission-line galaxies, many of which show clear evidence for AGN activity [1], [2], [9], [2].

Arguably the most convincing evidence for the obscured AGN model came from the ultra-deep survey of Hasinger, Schmidt et al. ([2], [2]). Using the Keck telescope to identify sources from the deepest X-ray observation ever taken they found that most of these X-ray galaxies could be classified as AGN. Exciting new work has also been undertaken at harder energies with ASCA and Beppo-SAX
resolving $\sim 30\%$ of the $2 - 10$ keV XRB. Increasing numbers of these sources have been identified with absorbed AGN.

2 Star-forming Galaxies and Submillimetre Surveys

Deep sub-mm observations offer the potential to revolutionise our understanding of the high redshift Universe. Beyond 100$\mu$m, both starburst galaxies and AGN show a very steep decline in their continuum emission, which leads to a large negative K-correction as objects are observed with increasing redshift. This effectively overcomes the ‘inverse square law’ to pick out the most luminous objects in the Universe to very high redshift [9]. Since the commissioning of the SCUBA array at the James Clerk Maxwell Telescope a number of groups have announced the results from deep sub-mm surveys, all of which find a high surface density of sources at 850$\mu$m ([44], [27], [7], [16], [10]). The implication is the existence of a large population of hitherto undetected dust enshrouded galaxies. In particular, the implied star-formation rate at high redshift ($z > 2$) is significantly higher than that deduced from uncorrected optical-UV observations, roughly a factor of two higher than even the dust-corrected version of the optically derived star-formation history [4]. The recent detections of the far-infrared/sub-mm background by the DIRBE and FIRAS experiments provide further constraints, representing the integrated far-infrared emission over the entire history of the Universe ([38], [21], [26]). Since most of this background has now been resolved into discrete sources by SCUBA, the implication is that most high redshift star-forming activity occurred in rare, exceptionally luminous systems.

In other words, at high redshift ULIRG-like starburst galaxies dominate the cosmic energy budget, in stark contrast to the situation today where (to quote Andy Lawrence) ‘ULIRGs are little more than a spectacular sideshow’ [32].

3 The X-ray/sub-mm link

Considerable excitement has been generated recently by the possibility that many of these SCUBA sources could be AGN. Whether these AGN are actually heating the dust is another matter (see Section 5) but there are now several independent lines of argument which suggest that AGN are present in a significant fraction of these SCUBA sources. At the very least, the implication is that much of the star formation in the high redshift Universe occurred in galaxies containing active quasars. First we present the arguments predicting an AGN contribution, followed by recent observational evidence.
3.1 Arguments for AGN in deep sub-mm surveys

- **The analogy with ULIRGs:** In many ways a significant AGN fraction would not be a surprise. The SCUBA sources are exceptionally luminous systems, essentially the high redshift equivalents to local ULIRGs. At the luminosities of the SCUBA sources ($\sim 10^{12}L_\odot$) we note that at least 30% of local ULIRGs show clear evidence for an AGN [40].

- **Predictions based on AGN luminosity functions:** One can estimate the AGN contribution by transforming the X-ray luminosity function to the sub-mm waveband using a template AGN SED. We estimate that $10^{-20}\%$ of the sources in recent SCUBA surveys could contain AGN, perhaps higher if one allows for Compton-thick objects [5]. Major sources of uncertainty are in the extrapolation of local AGN SEDs to high redshift, the dust temperature and in assuming the same underlying luminosity function for obscured AGN. Note that an independent but very similar analysis by Manners et al (in preparation) predicts a lower fraction ($5-10\%$).

- **Re-radiating the absorbed energy:** Another approach, also based on obscured AGN models for the XRB, does not rely on uncertain SEDs but instead on thermally re-radiating the absorbed energy directly in the far-infrared [23]. This method also predicts a significant AGN fraction among the SCUBA sources ($5-30\%$) although the exact prediction is strongly dependent on the assumed dust temperature.

- **SCUBA observations of high-z quasars:** Observations of the most luminous, very high redshift quasars ($z > 3$) suggest that many are exceptionally luminous in the far-infrared/sub-mm, with sub-mm luminosities comparable to Arp 220 [35]. Whether this emission is due to dust heated by the quasar or associated with starburst activity is unclear, but the lack of any correlation between the quasar power and the sub-mm luminosity would favour a starburst origin for the far-infrared emission. If one assumes that all high redshift quasars have similar sub-mm luminosities this would lead to a very large AGN fraction in the deep SCUBA surveys ($\sim 50\%$). In reality, however, some weak correlation between quasar power and the associated starburst is likely to exist, which would reduce this fraction significantly. Further sub-mm observations of high-z quasars are required to investigate these correlations.

3.2 Direct evidence for AGN in sub-mm surveys

- **The SEDs of detected SCUBA sources:** A recent analysis of the multi-wavelength spectral energy distributions (SEDs) of SCUBA sources has suggested that $\sim 1/3$ are likely to be AGN [13].

- **Spectroscopic identification:** Although the identification of many SCUBA deep survey sources remains elusive (perhaps indicating their exceptionally
high redshift) there are growing indications that a significant fraction harbour AGN. The first clear-cut identification turned out to be an obscured QSO and since then various surveys have been able to place limits on the AGN fraction. From a study of 14 sub-mm sources, Barger and collaborators have placed a lower limit of $\sim 20\%$ on the fraction showing evidence for AGN activity. Of seven sub-mm sources studied in detail by Ivison et al, at least 3 show evidence for an AGN. These estimates are in good agreement with the predictions of the various models outlined above.

4 Probing the X-ray/sub-mm link with Chandra and XMM

Forthcoming deep X-ray surveys with Chandra and XMM will push significantly fainter than ever before. In the soft X-ray band, we expect to reach at least an order of magnitude fainter than the deepest ROSAT surveys, while in the hard X-ray band the improvement is even more dramatic (Figure 1). The puzzle of the XRB should therefore soon be solved, and we expect to detect large numbers of obscured AGN and study their properties in detail. In addition, we will be able to detect typical quasars to very high redshift ($z \sim 8$) and hence assess the importance of quasar activity during those early epochs.

These deep X-ray observations are potentially ideal for identifying AGN in sub-mm surveys. The source densities expected are very similar ($\sim 1000$ deg$^{-2}$) and hence with the resolution of Chandra in particular it will be possible to pick out the AGN directly from their X-ray flux, with very little confusion.

The 8mJy survey of the UK SCUBA consortium is ideal for such a study (Figure 2). This is the only wide area SCUBA survey being conducted, covering 500 square arcminutes in 2 contiguous regions. One of these regions is in the Lockman Hole (which will be covered by Chandra in PV time). The other is concentrated on the N2 region of the ELAIS survey, where we have deep Chandra and XMM observations planned (PI: Almaini). We will be able to detect the hard X-ray emission from the hidden AGN and obtain a measurement of the absorbing column. If the equivalent width is high enough, in some cases XMM may even allow a redshift determination from an Iron line detection.

5 Conclusions and Implications

Several independent arguments now point to the conclusion that a significant fraction ($10 - 30\%$) of the luminous sub-mm sources detected by SCUBA will contain AGN. This points to a very important link between X-ray astronomy and the newly emerging sub-mm field, both of which provide probes of the obscured, high redshift Universe.
Figure 1: Predicted hard X-ray source counts for forthcoming Chandra surveys, compared with the deepest obtained so far (with ASCA and BeppoSAX).
Figure 2: Showing the N2 region from the UK SCUBA survey (small circles) in which we expect to detect $\sim 50$ submillimetre sources. This field is being observed for 75ks by Chandra (squares) and 150ks by XMM (large circle).
If a significant AGN fraction is confirmed with forthcoming Chandra/XMM surveys, considerable uncertainties will still remain. Is the dust heated by the AGN or by stellar processes? If the AGN is responsible, and their contribution is large, the recent conclusions about star-formation at high redshift may require significant revision. On the other hand the dust may be largely heated by stellar activity (see [39]) but with the interesting implication that much of the star formation at high redshift occurred in galaxies containing active quasars. It has recently been postulated that perhaps all quasars could go through an obscured phase during the growth of the black hole, a process which could be intimately linked with the formation of the galaxy bulge itself (see [19]). Future surveys combining X-ray and sub-mm observations will provide a powerful tool for disentangling these processes.

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